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FIELD MEASUREMENT AND MODEL EVALUATION PROGRAM FOR ASSESSMENT OF THE ENVIRONMENTAL EFFECTS OF MILITARY SMOKES

Evaluation of Atmospheric Dispersion Models for Fog-Oil Smoke Dispersion

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This report provides an evaluation of four of the most promising mathematical models for the prediction of the dispersion of fog-oil smoke discharged from M3A3E3 or M3A4 smoke generators. The data base used for model testing consists of seven data sets: three field trials conducted at Dugway Proving Ground, Utah during March/April 1985 and four field trials conducted at Camp Atterbury, Indiana in November 1987.

The results show that the four Gaussian puff models can predict within a factor of 2-3 under the convective and neutral conditions tested to distances of about 250 m. Beyond that distance, the plume tends to rise leading the models to significantly overpredict average concentrations at ground level. The model verification work shows that the particulate phase of a fog-oil plume acts like a tracer in its dispersion in the atmosphere -- for the short distances and stability classes tested with the Dugway and Camp Atterbury data.

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EXECUTIVE SUMMARY

Four Gaussian puff models were tested with seven field data sets collected on the dispersion of fog oil at two sites. Three data sets were obtained in flat terrain at Dugway Proving Ground and four data sets were acquired in generally flat terrain at Camp Atterbury near Columbus, Indiana. Data on average concentration over the time of release were obtained at distances of 25 m - 200 m at Dugway and 50 m - 675 m at Camp Atterbury. Data were acquired over several transects across the plume downwind from the source. In support of the in-plume average concentration measurements, there were time-dependent source measurements made along with time-dependent vertical profiles of meteorological data (mean values and turbulence quantities).

The models tested were the BEAR, INPUFF-Onsite, INPUFF-PG, and RIMPUFF. These models treat the release as a series of Gaussian puffs which get transported and dispersed downwind with a time-dependent wind field. The results show that the four Gaussian puff models tested can predict within a factor of 2-3 under the convective conditions tested to distances of about 250 m. Beyond that distance, the plume tends to rise leading the models to significantly overpredict average concentrations at ground level. No data were acquired at these two sites under stable conditions. (Fog-oil plumes were measured under stable conditions at the Meadowbrook site in Red Bluff, California but model testing with those data is not the subject of this report.)

One difficulty with the application of the above four models to the seven data sets is the simple nature of the Gaussian models tested. Indeed, simple models are needed for the practical and rather routine smoke plume modeling used by the U.S. Army. However, simple models usually require simple inputs such as a single-level wind speed as a function of time. Should the wind speed at the release height be used or is the 10-m value more representative? An entire profile of such meteorological data is available from the experiments. What is the initial puff radius and height above the ground once the initial momentum of the plume exiting the three release ports is accounted for? There are no definitive answers to such questions (known at this time) and the models are sensitive to the choices made. In any case, the agreement between the models and data is reasonable for such flat terrain applications and distances equal to or less than about 250 m.

Although the Gaussian models tested with the fog-oil data indicated an overall agreement with the data within a factor of 2-3 for the average concentrations measured, there were problems with the models (under these largely unstable atmospheric conditions) in that

(i) such agreement was only within the first 250 m from the smoke generator with more significant discrepancies at further distances,

(ii) there is a tendency to significantly overpredict or underpredict average concentrations at distances less than 100 m and to significantly overpredict at distances greater than about 250 m. The discrepancies found at longer distances (greater than about 250 m) is due to a rise in the plume centerline, and

(iii) the decay of concentration with distance as predicted by the models does not agree with the data and is likely to be the result of the rising centerline seen in the observed plume. The rising centerline phenomenon has been observed in other field and laboratory studies and cannot be predicted by these Gaussian models.

In a companion report, a stochastic model is compared to the Camp Atterbury data and is shown to predict the rise of the plume under convective conditions quite well along with the correct decay of concentration with distance. The lack of treatment of convective turbulence in the Gaussian puff models is apparently the cause of the discrepancies between the model predictions and the data beyond about 250 m. Future work will involve the testing of complex terrain versions of these types of models with both the stable and unstable plume dispersion data at the Meadowbrook site.

ACKNOWLEDGMENTS

We thank the model developers Dr. Torben Mikkelsen (for RIMPUFF), Dr. Frank Ludwig (for BEAR), and Mr. William Petersen (for INPUFF) for their assistance in providing us with the computer codes to their models and for their time in answering questions on the proper application of their models to our smoke data.

We also wish to thank our USABRDL Project Officers, Major David Parmer and Major John Young for their important role in shaping this project. Their many helpful suggestions and insightful comments added enormously to the success of the effort.

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LIST OF SYMBOLS

SYMBOL	MEANING
cm	centimeters
CDT	Central Daylight Time
C/m	degrees Centigrade per meter
deg	degree
E	east
g/s	grams per second
k	von Karman constant
kg	kilograms
L	Monin-Obukhov length
MDT	Mountain Daylight Time
mg/m^3	milligrams per cubic meter
N	north
PGT	Pasquill-Gifford-Turner stability class
u^*	friction velocity
U	mean wind speed
w^*	convective velocity
z_i	height of mixing layer
ΔT	temperature difference between the 2-m and 10-m levels on a meteorological tower
σ_θ	standard deviation in horizontal wind direction
σ_ϕ	standard deviation in vertical wind direction
θ	mean wind direction

1.0 INTRODUCTION

This report provides an evaluation of four of the more promising mathematical models for the prediction of the dispersion of fog-oil smoke discharged from M3A3E3 or M3A4 smoke generators. The data base used for model testing consists of seven data sets: three field trials conducted at Dugway Proving Ground, Utah during March/April 1985 (Liljegren et al., 1988) and four field trials conducted at Camp Atterbury, Indiana in November 1987 (Liljegren et al., 1989).

The purpose of the model evaluation portion of the current research program is to identify the superior modeling approaches and individual models for fog-oil smoke dispersion. Some model improvement may be necessary to satisfy the objectives of the U.S. Army. Such validated model(s) could then be used in two ways:

(a) In environmental impact analyses to determine the health and environmental effects of smokes used in training exercises carried out by the U.S. Army. Of greatest interest here is the prediction of dosage (time-integrated concentration), particle-size distributions, and deposition rates at distances just downwind of the generator (e.g., 20m) to several kilometers downwind, and

(b) During the execution of training exercises with smokes. In such circumstances, the model(s) would be used in a real-time mode to determine whether a specific fog-oil trial should be undertaken given current meteorological conditions. The prediction of the extent of the visible plume would be useful as well as the quantities identified in (a).

The measurement program undertaken at Dugway Proving Ground and Camp Atterbury was aimed at providing the data in (a). Color video photographs of the plume were taken at both sites; however, plume visibility was not an objective of either set of field tests and so only qualitative information on plume visibility was obtained.

An early evaluation of fog-oil plume models was carried out as part of the current program (Policastro et. al., 1985). In that work, four models were tested with three data sets from Smoke Weeks III and IV. The models were Act II (Sutherland et al., 1982 and Petraska, 1984), MAD PUFF (Petraska, 1984), COMBIC (Hoock et al., 1982), and Ludwig (Ludwig, 1977). Although there was not a large difference among the predictions of the models, it became clear that models that could handle time-varying meteorology would be the most useful considering the dual purposes (see (a) and (b) above) that the modeling must satisfy. The model/data comparisons provided in that paper (Policastro et. al., 1985, and also Appendix A of this report) could not lead to any definitive conclusions because:

(i) The Smoke Week III and IV data for dosage were adjusted subjectively by Dugway personnel in order to provide more physically reasonable data. The amount of this correction or adjustment is unknown and casts doubt as to the accuracy of that data base, and

(ii) The data were acquired at distances only within about 90 m from the source and involved generator run times of only a few minutes.

The three data sets acquired during the March/April 1985 time period at Dugway Proving Ground and the four data sets acquired during the November 1987 time period at Camp Atterbury, Indiana provide new sources of data for model testing. Measurements were made to slightly longer distances (out to 200 meters at Dugway and out to 675 meters at Camp Atterbury) and for generator run times close to one hour. No adjustments were made to these data in any way.

Presented below is a description of the three models tested with these data and the results of the model/data comparisons.

2.0 THE MODELS

An examination of the literature reveals that there are three general modeling approaches that can be used to simulate the dispersion of fog-oil plumes. These are:

(a) Gaussian puff method

In this treatment, a continuous release is divided up into a number of puffs whereby each puff is advected and dispersed downwind based on time-dependent meteorology. Models within this category differ based largely upon the dispersion coefficients used as well as wind speeds (wind field) employed. This technique has the advantage of handling a variable source release rate which is common with U.S. Army smoke generators. Models in this category are Ludwig (Ludwig, 1977), RIMPUFF (Mikkelsen et al., 1984), and INPUFF (Petersen, et al. 1984). Note, the Ludwig model is also known as the BEAR model. This approach is amenable to handling time-dependent meteorological data from a tower at the site of interest.

(b) Gaussian plume method

This methodology assumes that the continuous Gaussian plume formulation can best represent the fog oil release. The treatment of long release times is handled through the dependence of the dispersion coefficients (σ_x, σ_y, and σ_z) with release time. For large release times, for instance, the σ_y coefficient is large leading to a wider plume. That same plume might just as well have been predicted by the Gaussian puff method with many puffs being spread out in different wind directions over that long release time, with each puff having a small σ_y. It is not a priori clear whether the Gaussian plume method can be as accurate as the Gaussian puff method for the long release times expected for fog-oil plumes. Models that are represented in the category of Gaussian plume method are: ACT II (Sutherland et al., 1982 and Petraska, 1984), MAD Puff (Petraska, 1984), COMBIC (Hoock et al., 1982), MSMOKE (Hansen, 1984), HZRD II(Pennsyle, 1984), and HECSMOKE-I (Cheney and Dumbauld, 1979).

(c) Monte-Carlo method

This methodology represents the fog-oil release as the emission of large numbers of particles that are advected and dispersed with the wind. The advantage to this method is that it is better suited to handling the more fundamental aspects of atmospheric turbulence (does not rely on Gaussian dispersion coefficients as do the other two methods) and can more accurately treat surface boundary conditions. This method is more suitable in complex terrain situations as well. Unfortunately, the existing models in this category must still be considered as research tools and are only now entering the competitive arena with the Gaussian puff and plume models. Models in this category are MoCaPD (Huang and Frost, 1982), Dunn-Boughton (Boughton and Dunn, 1983) and Schorling (Schorling, 1986).

2.1 Models Evaluated

For the purposes of this evaluation of models with the Dugway and Camp Atterbury data, three Gaussian puff models have been chosen for testing. They are BEAR, INPUFF, and RIMPUFF. These models satisfy the criteria of handling time-dependent meteorological data and ease of use.

The simplest of the three models is the BEAR model. This model permits as input time-dependent meteorological data for use in dispersing puffs. Each time that meteorological inputs are read, a new time step for the release of puffs is determined. The model permits the simulation of changing wind speeds and directions during the period of smoke generation. As a result, plume meander is treated by means of this time-dependent formulation. The Gaussian puff dispersion coefficients employed in the model are the Pasquill-Turner coefficients that are dependent on stability class. Although developed for continuous plumes, they are applied by Ludwig to puffs. Meteorological data are read into the model in three minute time steps, consistent with the averaging time of the Pasquill-Gifford-Turner dispersion coefficients (Turner, 1970).

The RIMPUFF model is similar in its formulation to the BEAR model. However, the dispersion coefficients are functions of downwind distance based on either:

(a) the Pasquill-Gifford-Turner stability class, or

(b) the variances in the wind direction using the work done by Smith and Hay (1961).

In this model, meteorological time steps are typically 15 seconds with the dispersion coefficients adjusted to that time scale. In this way, plume meander is simulated directly from the variation of wind direction with time. Meander is not included in the dispersion coefficients.

The INPUFF model is also similar to BEAR and RIMPUFF in that it divides the release into a series of puffs. For smoke applications, the meteorological time step is typically 2-3 minutes. The puff release rate is independently set and may be chosen to be once every 10 seconds. This dichotomy parallels that of the Ludwig model. Three dispersion algorithms are used within INPUFF for dispersion downwind of the source. The user may use the Pasquill-Gifford-Turner (P-G) scheme or the On-Site scheme, so named because it requires specification of the variances of the vertical and lateral wind direction. The On-Site scheme is a synthesis of work performed by Draxler (Draxler, 1976) and Cramer (Cramer, 1976). The third dispersion scheme is for long travel times in which the growth of the puff becomes proportional to the square root of time.

The treatment of the wind field for a typical smoke release is handled in the following way with these models. The BEAR model requires the input of the 10-m level wind speed, wind direction, and relative humidity as a function of time. The model handles only one time series of measurements at only one level. The BEAR model requires the meteorological data to be input as roughly three-minute averages, in concert with the averaging time of the dispersion coefficients.

For RIMPUFF, meteorological input is more general. That model can handle multiple meteorological stations; however, each station must have its time series of data provided at only one level. The data, however, may be taken at different reference heights whereby the model interpolates all to a single inputted reference height. The input height of the meteorological measurements for this model is not fixed at 10 meters as in the other models, rather any height can be specified and the model will create a vertical wind profile from the chosen reference height. The model computes the u and v wind components on a grid; $1/r^2$ interpolation in space and linear interpolation in time is used to provide the wind speed components at each grid point at each meteorological time step. The wind field created in this manner will not necessarily be divergence free.

For INPUFF, the user must supply the wind speed and direction within a grid system. The user defines the coordinate and size of each grid square as well as the extent of the meteorological region. The meteorological region may be larger or smaller than the modeling region. The meteorological data (wind speed, wind direction, σ_θ, σ_ϕ , mixing height, and stability class) are read in as a function of time. The P-G scheme does not use σ_θ and σ_ϕ values, while the On-Site scheme does not use the stability class. A meteorological preprocessor definea by the user may compute (single-layer) winds and the output of that preprocessor may be input into INPUFF.

For a single meteorological tower supporting a smoke experiment, all three models can have their wind field treatment reduce to an identical formulation: the 10-m wind level as a function of time. The averaging period for that 10-m level data will, of course, be different depending upon the model due to the needs of its dispersion scheme.

For the Dugway and Camp Atterbury tests, the models being tested are similar in many ways with the main exception being in their treatment of the dispersion of the puffs. For each of the models, coding changes were made to predict dosage at each receptor. Each model had predicted concentration with time. Table 2.1 gives a comparison of the theoretical features of these three models.

3.0 THE DUGWAY FIELD DATA

This section provides a short summary of the data acquired in the March/April 1985 field tests at Dugway Proving Ground (Liljegren et al., 1988). Three data sets are used for model testing in the next section. More details concerning all the data acquired as well as the equipment and methodology used is given in Liljegren et al.(1988).

Table 2.1 Comparison of theoretical features of the INPUFF, BEAR, and RIMPUFF Models

Feature	INPUFF	BEAR	RIMPUFF
Wind Field	provided by user, variable in space and time	single point and elevation but variable with time	multiple station measurements interpolated in space and time
Dispersion Methodology	Gaussian puff	Gaussian puff	Gaussian puff
Dispersion Coefficients	PGT stability classes (f) or on-site scheme (a)	PGT stability classes(f)	PGT stability classes(f) or on-site scheme (b)
Meteorological Time-Averaging Period (c)	2-5 minutes	3 minutes	15 seconds
Puff Release Interval (d)	1 second	1 second	1 second
Treatment of Wind Shear on Puff Dispersion (e)	No	No	Yes
Source Conditions:			
Time Dependent	Yes	No	Yes
Multiple Sources	Yes	No	Yes

(a) The on-site scheme uses σ_θ and σ_ϕ measurements in formulas for σ_y and σ_z derived by Irwin (1983) from a combination of the Draxler (1976) and Cramer (1976) formulas.

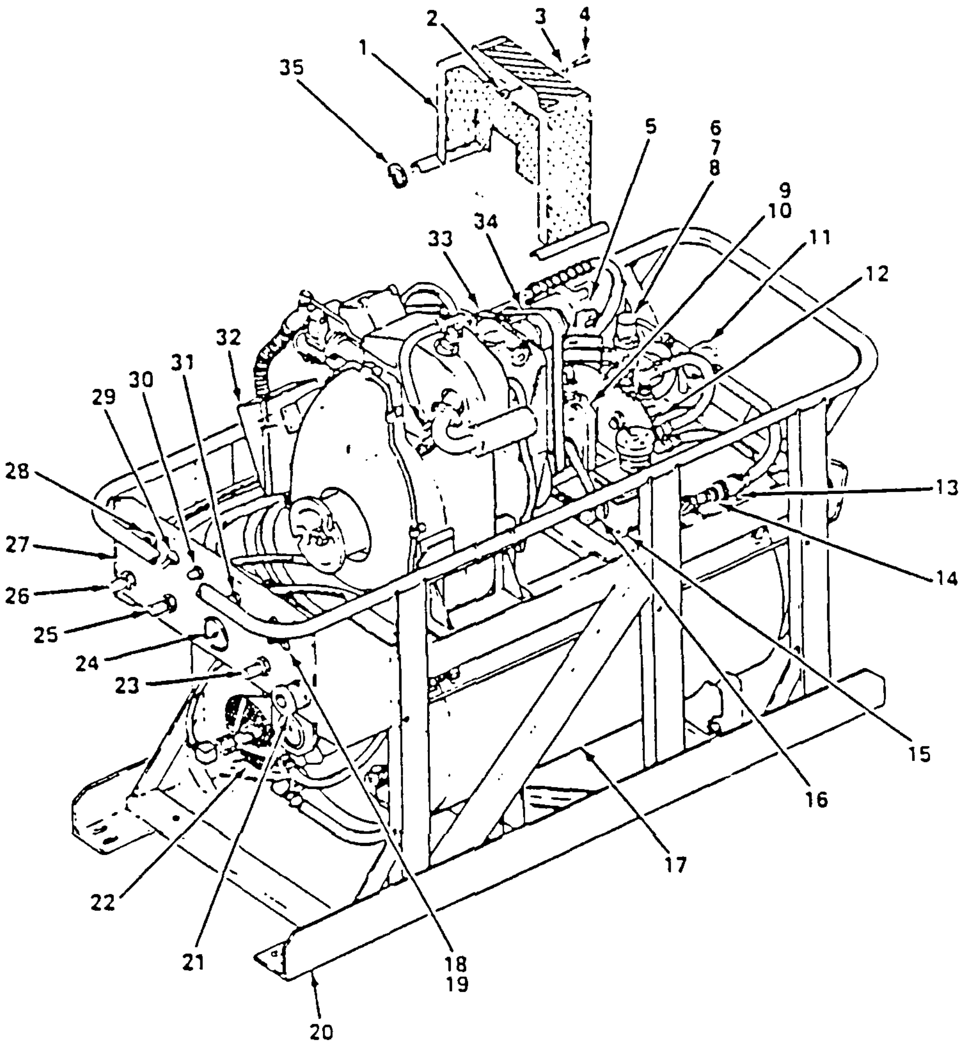
(b) The on-site scheme here employs σ_θ numbers in the Smith-Hay dispersion formulas (1961).

(c) The times provided here are recommended by the modelers based on the dispersion coefficients used in the model. The INPUFF (PG scheme) and the BEAR Model use the same dispersion coefficients.

(d) The one second values are the lowest values that are recommended by the modelers. Larger values reduce computer time but also reduce prediction accuracy dependent upon the extent of departure from the 1 second values.

(e) Ignoring the effect of wind shear on individual puff dispersion leads to a Gaussian distribution in the vertical direction. The RIMPUFF Model does not yield a Gaussian distribution in the vertical direction as a result of its treatment of vertical wind shear on plume dispersion.

(f) PGT stability classes refer to Pasquill-Gifford-Turner stability classes A-F, where A represents the most unstable conditions and F the most stable conditions.



1 BELT GUARD ASSEMBLY
2 NUT
3 WASHER
4 SCREW
5 FOG OIL PUMP ASSY
6 FOG OIL CONTROL VALVE
7 SWIVEL NUT TEE ASSY
8 MALE ELBOW
9 COMBUSTION IGNITION MAGNETO
10 MAGNETO PULLEY
11 HOT GAS ISOLATOR
12 UNLOADER VALVE ASSY
13. LOOP CLAMP
14 PRESSURE SWITCH
15. AIR COMPRESSOR ASSY
16 BELT
17 PULSE JET ENGINE ASSY
18 GLOBE VALVE
19 MALE ELBOW
20. FRAME ASSY
21 QUICK DISCONNECT
22. NOZZLE ASSEMBLY
23. QUICK DISCONNECT
24 AIR PRESSURE GAGE
25. QUICK DISCONNECT
26. QUICK DISCONNECT
27 CONTROL PANEL
28. TOGGLE VALVE
29 SWITCH
30. PURGE AIR SWITCH
31 START AIR SWITCH
32. ENGINE ASSY
33. FUEL PUMP ASSY
34 BELT
35. HOSE CLAMP

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Figure 3.1 M3A3E3 Smoke Generator assemblies and major components (from M3A3E3 Operations Manual).

Table 3.1. Summary of source release data for Dugway fog oil smoke tests

Test	Date/Time	Source Coordinates (m)	Generator Run Time (s)	Emission Mass (kg)	Emission Rate (g/s)	Emission Rate (gal/hr)	Exit Velocity (m/s)
T0009	9-Apr-85 13:38 - 14:53	-3.7, 30, 1.2	4140	179.0	43.2	45.8	66.6
T0010	10-Apr-85 14:20 - 15:38	400, 0, 1.2	3720	155.0	41.7	44.2	73.2
T0011a	11-Apr-85 9:38 - 9:45	-4.0, 0, 1.2	420	16.0	38.1	40.4	74.6
T0011b	11-Apr-85 10:30 - 11:55	-4.0, 24, 1.2	5100	192.0	37.6	39.9	74.6

Notes:
1. Tests marked "a" and "b" have been divided in two to account for changes in the wind direction.
2. For tests T0010 and T0011, the mass released was determined from the initial and final weight of the oil drum.
3. Run times may be less than the difference between the start and end times due to failures of the M3A3E3.

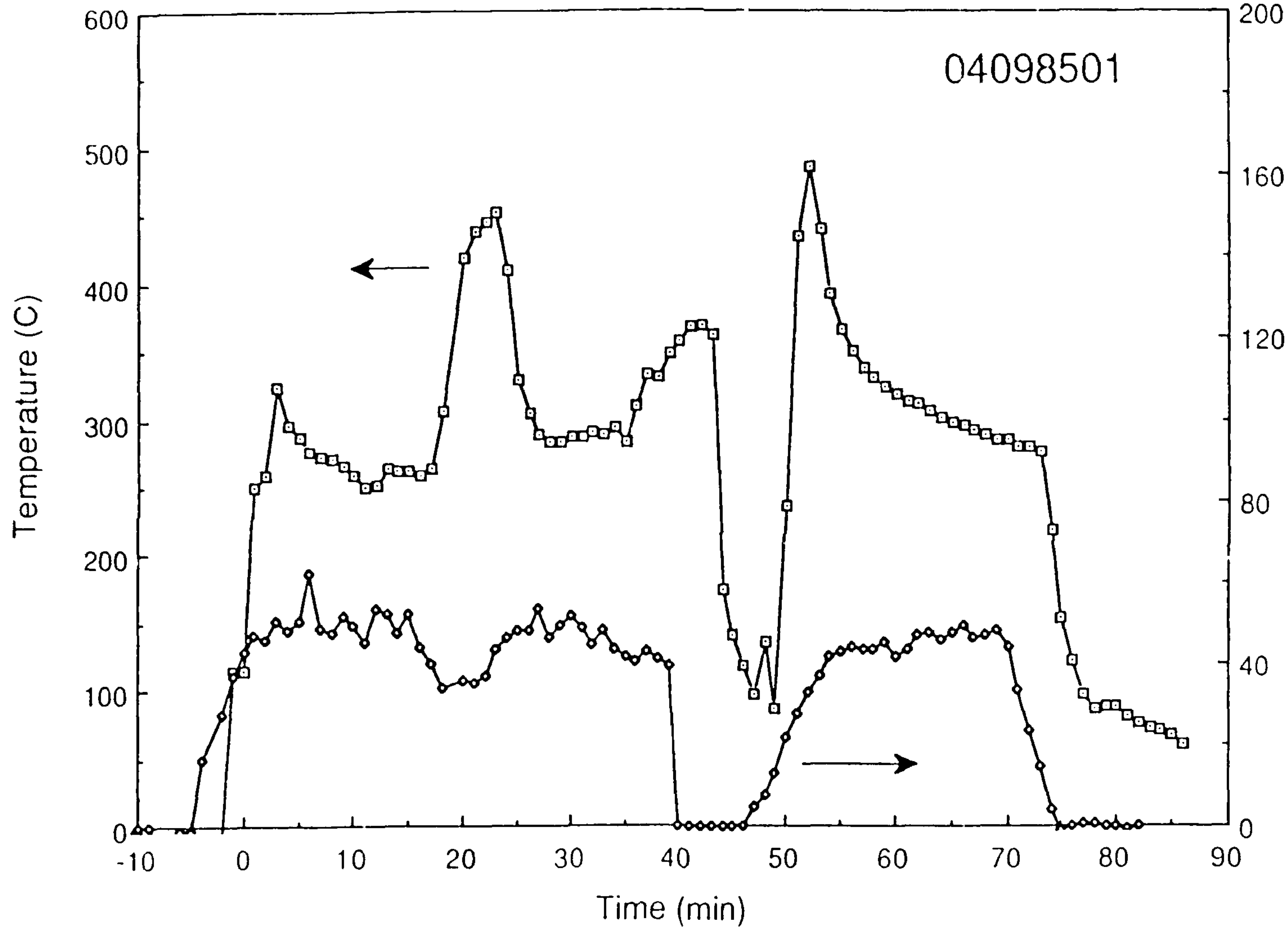


Figure 3.2. Exit tempe·ature (°C) and release rate (g/s) as a function of time for test T0009 (9 Apr 1985).

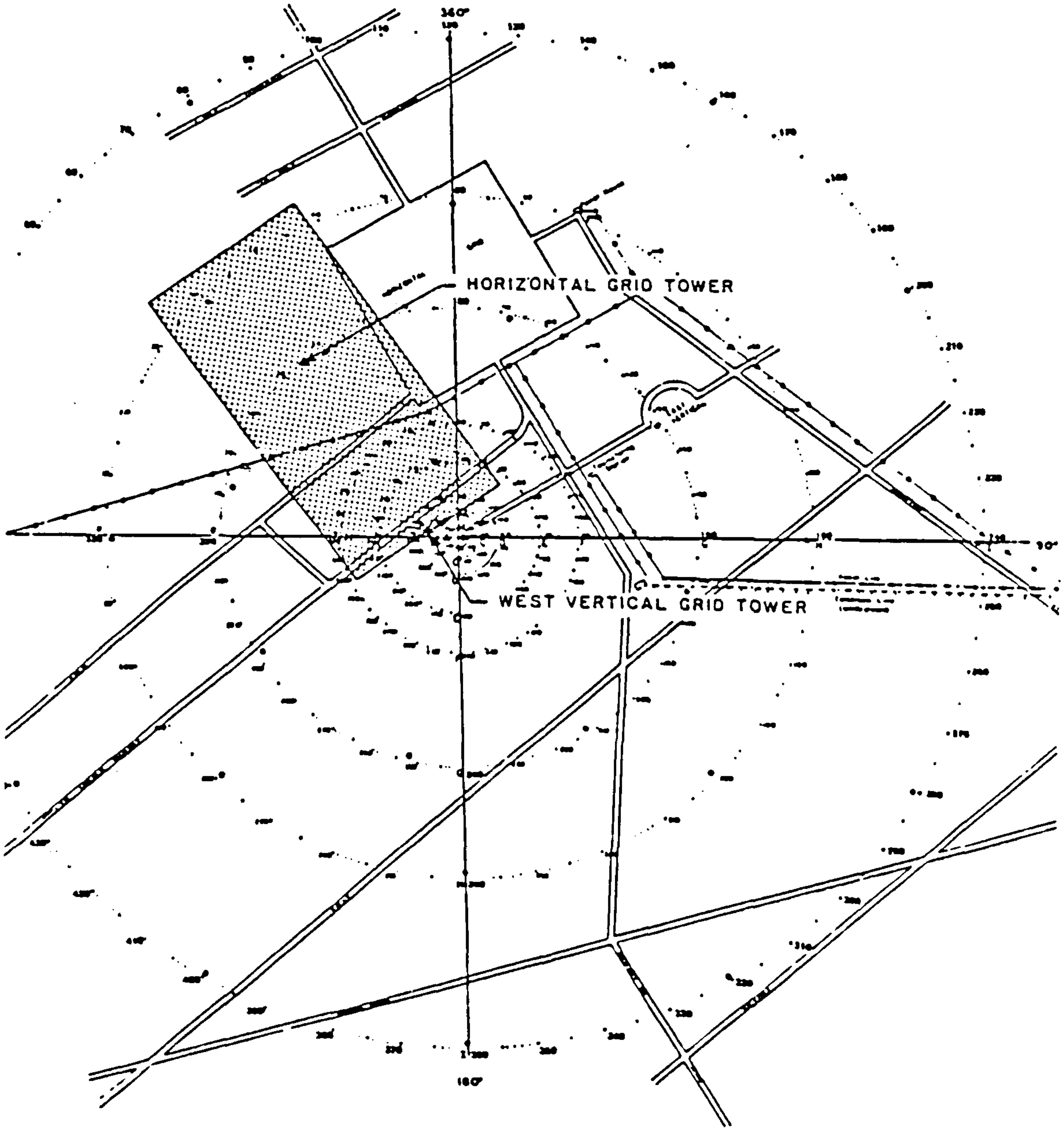


Figure 3.3. Location of test site with respect to Horizontal and West Vertical grids at Dugway Proving Ground. The sampling network is located in the shaded portion of the figure.

All three tests employed a M3A3E3 military smoke generator (see Figure 3.1). It produces smoke by vaporizing fog oil and ejecting it into the atmosphere. Time-dependent measurements of exit temperature were taken by instrumenting each of the three exit nozzles on the generator with a chromel/alumel (type k) thermocouple. Estimates of the exit velocity of the smoke were obtained periodically during a test using a pitot tube. The calculation of the exit velocity accounted for the high temperature of the exhaust stream as well as the increased density of the exhaust stream due to the fog oil. A scale was used to provide the remaining weight of fog oil in a 55 gallon drum as a function of time.

A summary of the data acquired at the source for the three experiments is given in Table 3.1 with an illustration of the time-dependent source data given in Figure 3.2. Note that the release rate varied significantly during the test. This highlights the need for time-dependent mass release data and a model that can treat that time-dependent release.

The meteorological data were collected from two 32-m towers located at the Dugway test site (see Figure 3.3). The test site for the fog-oil smoke release was located between the meteorological instrument towers on Horizontal Grid and West Vertical Grid. The site of the testing passes the micrometeorological test of uniform terrain in all directions to a distance equal to 100 times the tower heights. The roughness length for the site is 2 cm. The primary vegetation for the site is a desert shrub having a height of 7 to 30 cm and spaced at one-half to one meter intervals.

At each tower, wind speeds were measured with cup anemometers at 2, 4, 8, 16, and 32m. Fluctuations in the horizontal and vertical wind angles were measured with bivanes mounted at 4, 8, 16, and 32m. Horizontal wind fluctuations at the 2m level were measured with a direction vane. On both towers, temperatures were measured at the 2, 4, 8, 16, and 32m levels. The meteorological data on both towers were available at one second intervals. A summary of the meteorological data acquired during the three tests is given in Table 3.2. Considering that only three test data sets were to be compared with model predictions, a comparison of the acquired meteorological data with long-term stability class / wind speed data at Dugway Proving Ground was not found to be fruitful.

The location of the sampling network within the West Vertical Grid is illustrated by the shaded region in Figure 3.4. A high resolution network was laid out in the shaded area of Figure 4 between rows 2 and 6 and columns J and N (see Figures 3.4 and 3.5). As illustrated in Figure 3.5, this network is essentially diamond-shaped. It is composed of transects at 25 m, 50 m, 100 m, 200 m, and 400 m and is symmetric about the 200 m transect. Eleven samplers were located on both the 25 m and 50 m transects at spacings of 5 m and 10 m respectively. Nine samplers were located on the 100 m, 200 m, and sampling plan, the smoke source could be located near J4(0,0) or N4(400,0) depending on the wind direction. At each sampler placed on operation, total mass of fog oil collected was measured. More details about the sampling system appear in the Dugway data report (Liljegren et al, 1988).

Average concentration for test cases T0090, T0010, and T0011 are summarized in the isopleth plots presented in Figures 3.6,3.7, and 3.8. Note that for test T0011 (11 April 1985), the wind direction changed while the generators were being field repaired after breakdown. To accommodate this wind shift, the generator was relocated prior to restarting the test; both locations are indicated in Figure 3.8. Model predictions will be compared to the data on a transect basis in the next section of this report.

4.0 COMPARISON OF MODELS WITH FIELD DATA TAKEN AT DUGWAY PROVING GROUND

Application of the BEAR, RIMPUFF, and INPUFF models to these three data sets was accomplished in a straight-forward manner. The meteorological data for these three data sets were available on a one second basis from Dugway Proving Ground from which time averages were prepared based on the appropriate averaging of meteorological data required by each model. Next, the time series of mass release of fog oil was input for both schemes of the INPUFF model, with a time averaging period of 3 minutes. The RIMPUFF and BEAR models employ only one (average) mass release rate. Both the BEAR and the INPUFF models used a time averaging period of 3 minutes for the meteorological data, while the RIMPUFF model used a time averaging period of 15 seconds.

Table 3.2. Summary of meteorological data for the three Dugway data sets

Test Designation	T0009	T0010	T0011a	T0011b
Date	9-Apr-85	10-Apr-85	11-Apr-85	11-Apr-85
Begin Release (MDT)	13:38	14:20	9:38	10:30
End Release (MDT)	14:53	15:38	9:45	11:55
Wind Speed (m/s)	5.2	2.6	7.2	6.3
Wind Direction (deg)	11 E of N	201 E of N	338 E of N	5 E of N
Sigma-u (m/s)	1.7	1.2	1.3	1.7
Sigma-theta (deg)	18.7	43.9	11.0	14.7
Sigma-phi (deg)	8.8	15.7	4.8	7.1
Sigma-v (m/s)	1.6	1.5	1.4	1.5
Sigma-w (m/s)	0.7	0.6	0.6	0.7
Ambient Temp (C)	18.5	22.7	16.0	18.2
Lapse Rate (C/m)	-0.0403	-0.0196	-0.0438	-0.0517
Rel. Humidity (%)	23	21	36	31
Stability Class	C	B	D	C
Monin-Obukhov Length (m)	-19	-2.2	-107	-22
Wind Power Exponent	0.114	0.093	0.150	0.0120
Friction Velocity (m/s)	0.34	0.22	0.42	0.41
Roughness Height (cm)	2	2	2	2

Notes: 1. All values are averages over the period of the test.

2. All values are for the 10 m level except for the relative humidity which is reported for the 4 m level

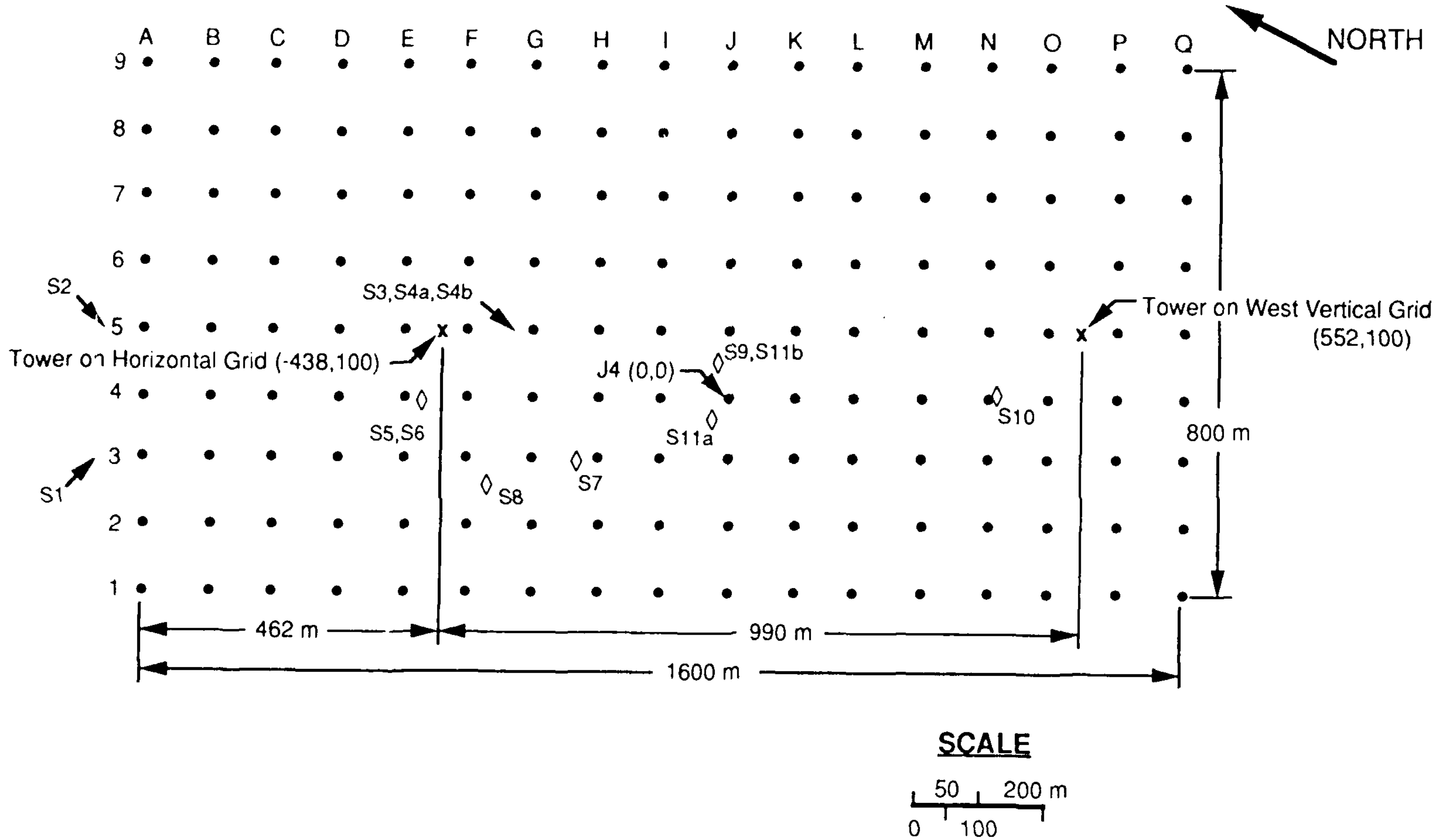


Figure 3.4. Layout of main sampling network and coordinate sytem. Filled circles indicate sampler locations. Diamonds (◊) indicate sources. Shaded areas locates High Resolution Network illustrated in Figure 3.3

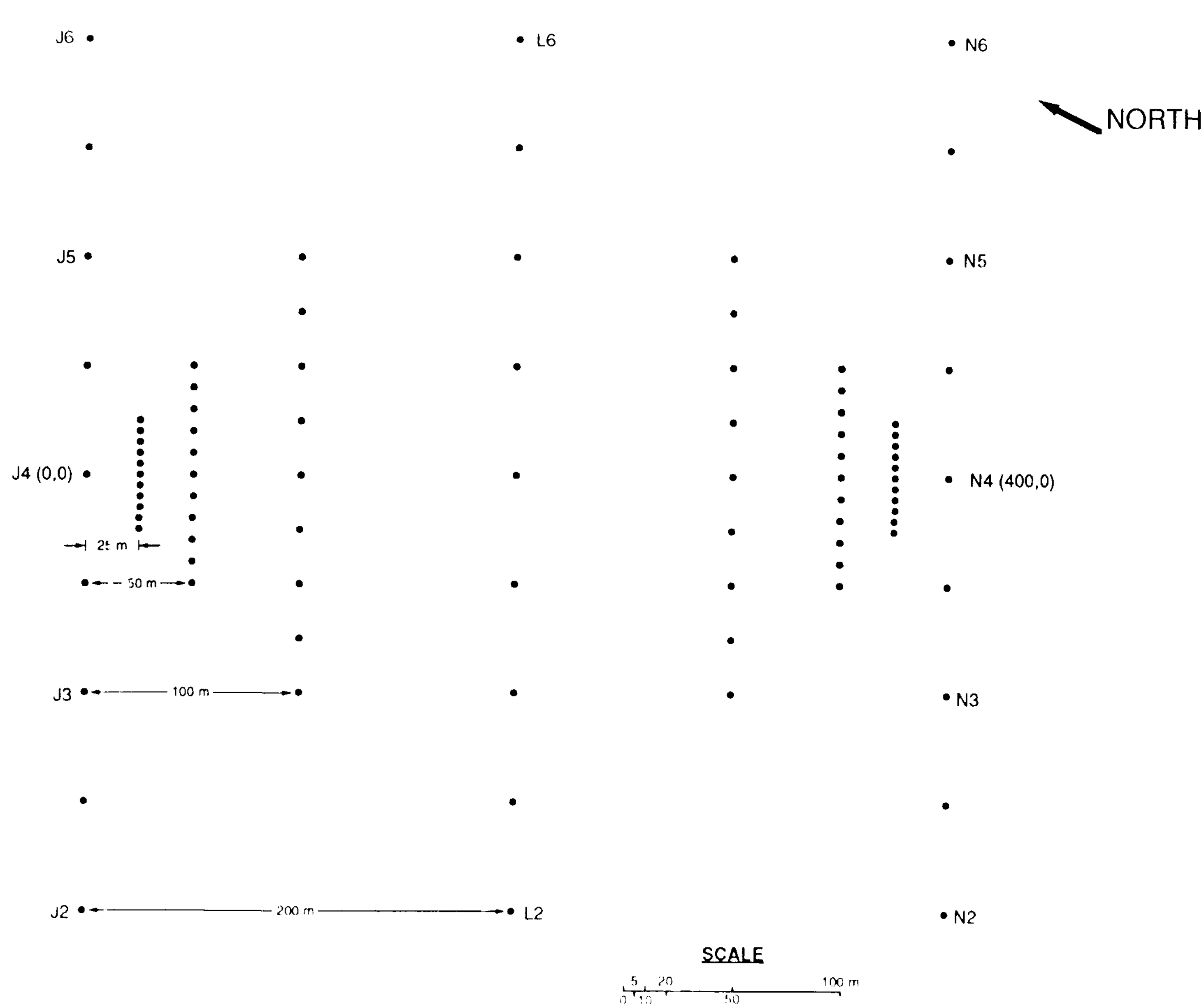


Figure 3.5 High resolution sampling network indicated by the shaded area in Figure 3.3. Filled circles marked the locations of concentration samplers.

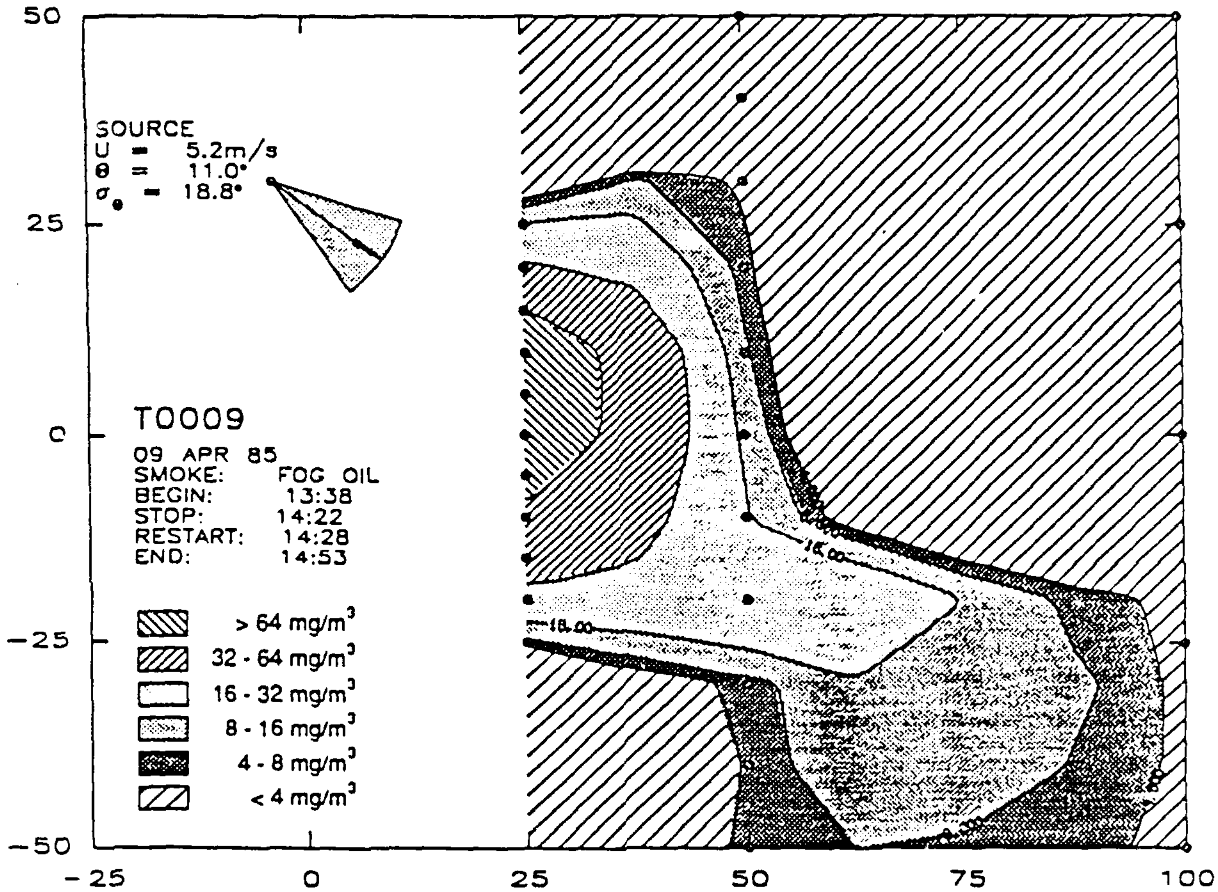


Figure 3.6. Isopleths of average concentration for test T0009. Sampler locations are indicated by small filled circles. The arrow at the source location indicates the mean wind direction; its length is proportional to the mean wind speed. The shaded sector around the arrow indicates the mean wind direction; its length is proportional to the mean wind speed. The shaded sector around the arrow indicates the standard deviation of the wind direction.

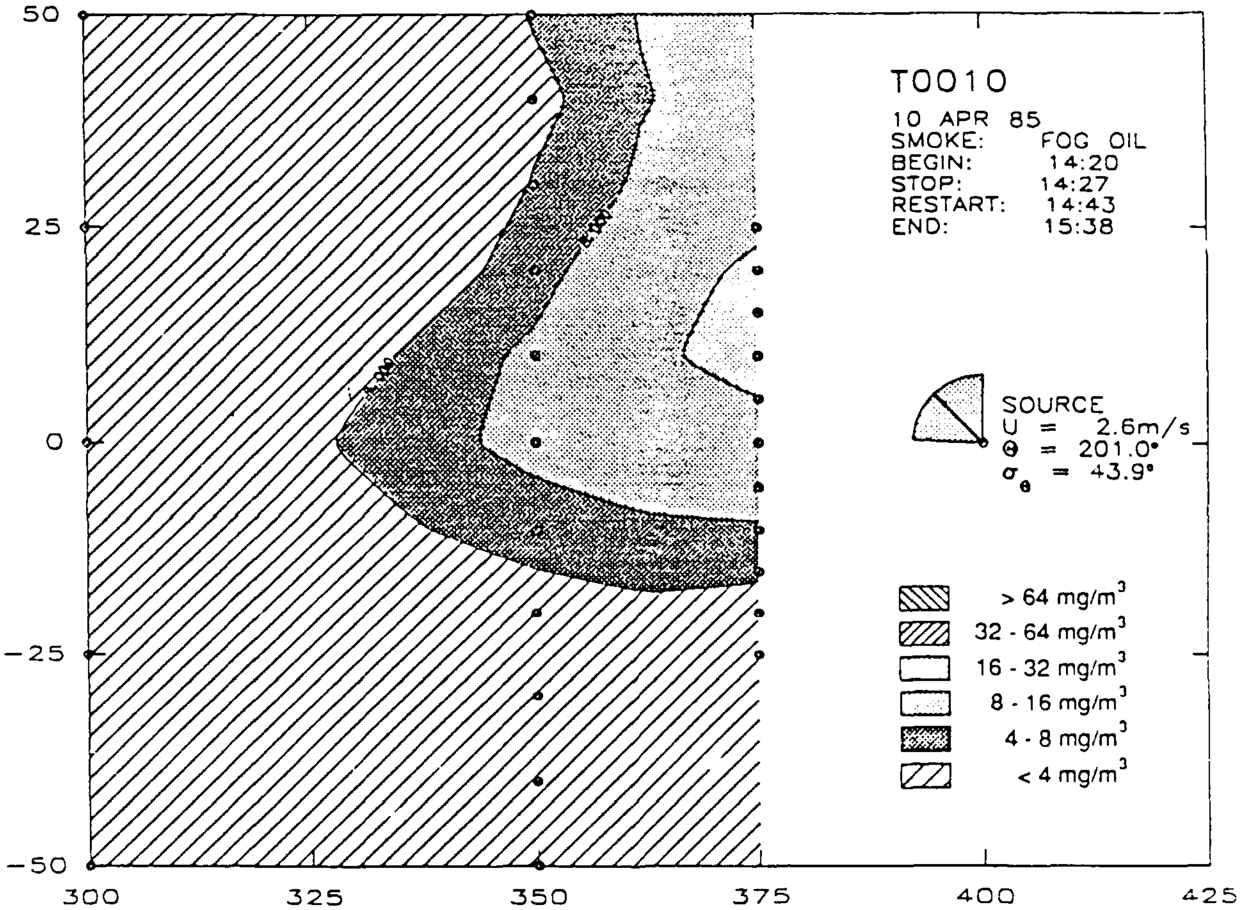


Figure 3.7. Isopleths of average concentration for test T0010. Sampler locations are indicated by small filled circles. The arrow at the source location indicates the mean wind direction; its length is proportional to the mean wind speed. The shaded sector around the arrow indicates the standard deviation of the wind direction.

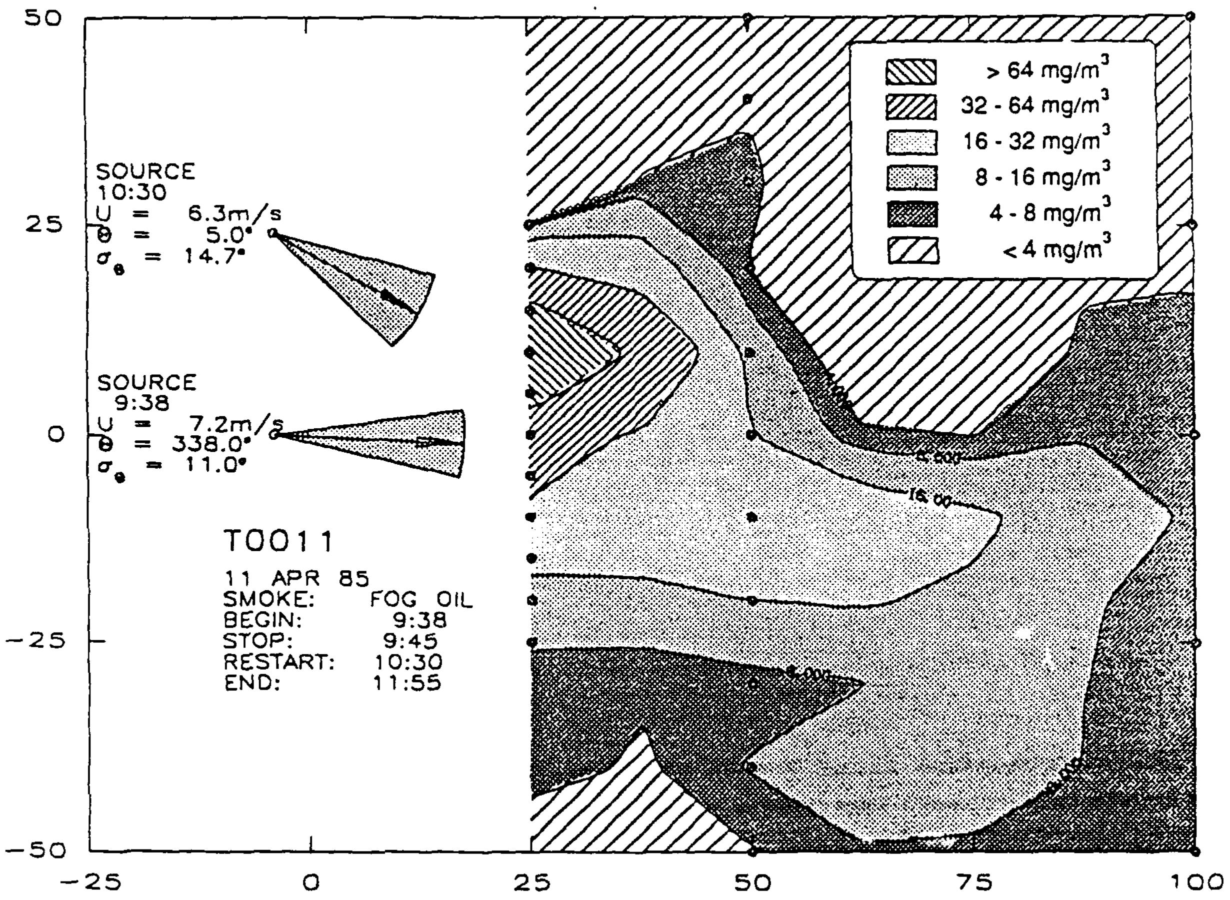


Figure 3.8. Isopleths of average concentration for test T0011. Sampler locations are indicated by small filled circles. The arrow at the source location indicates the mean wind direction; its length is proportional to the mean wind speed. The shaded sector around the arrow indicates the standard deviation of the wind direction.

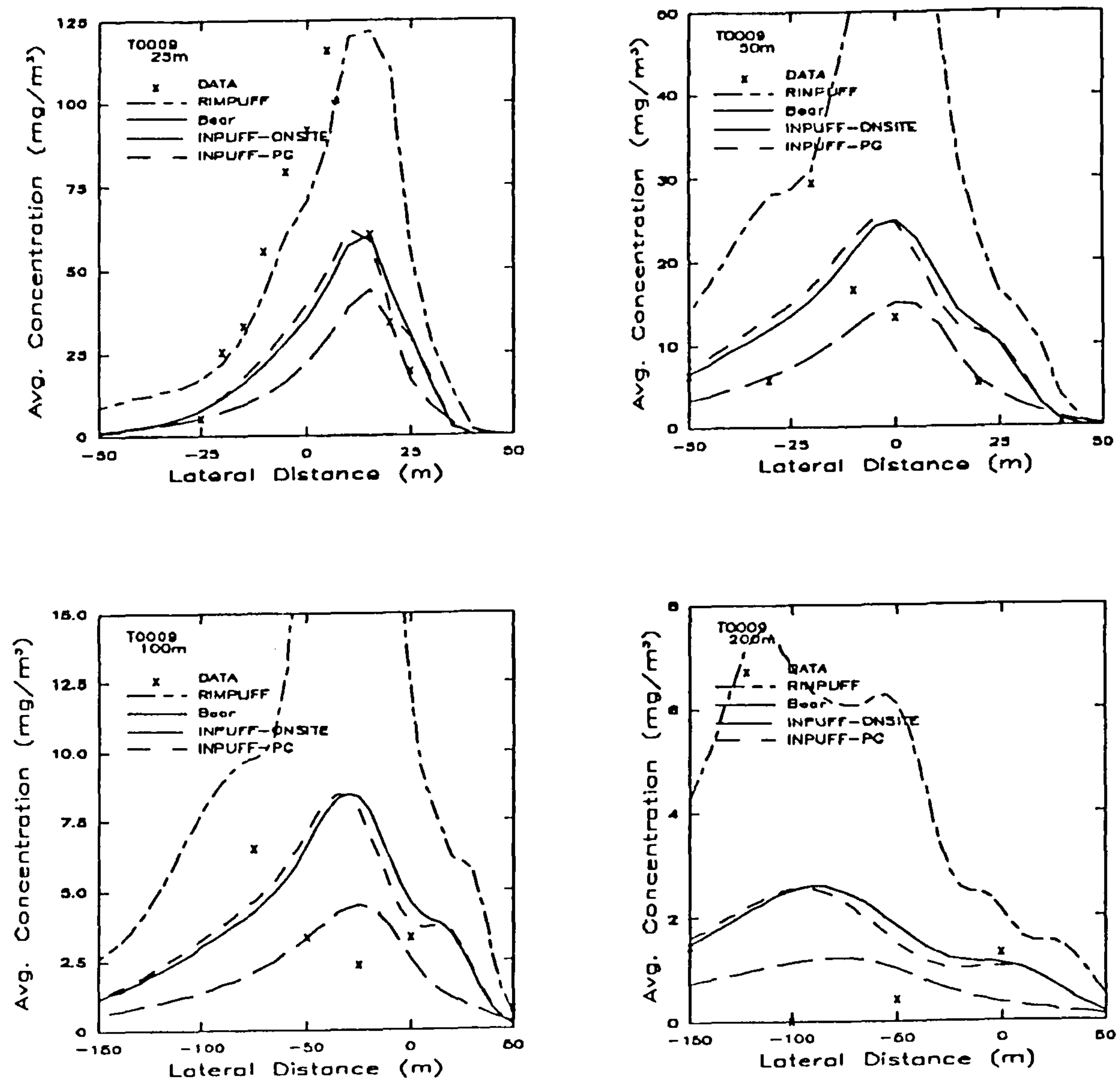


Figure 4.1. Comparison of RIMPUFF, BEAR, INPUFF-Onsite and INPUFF-PG mathematical models with average concentrations from test T0009 at Dugway Proving Ground.

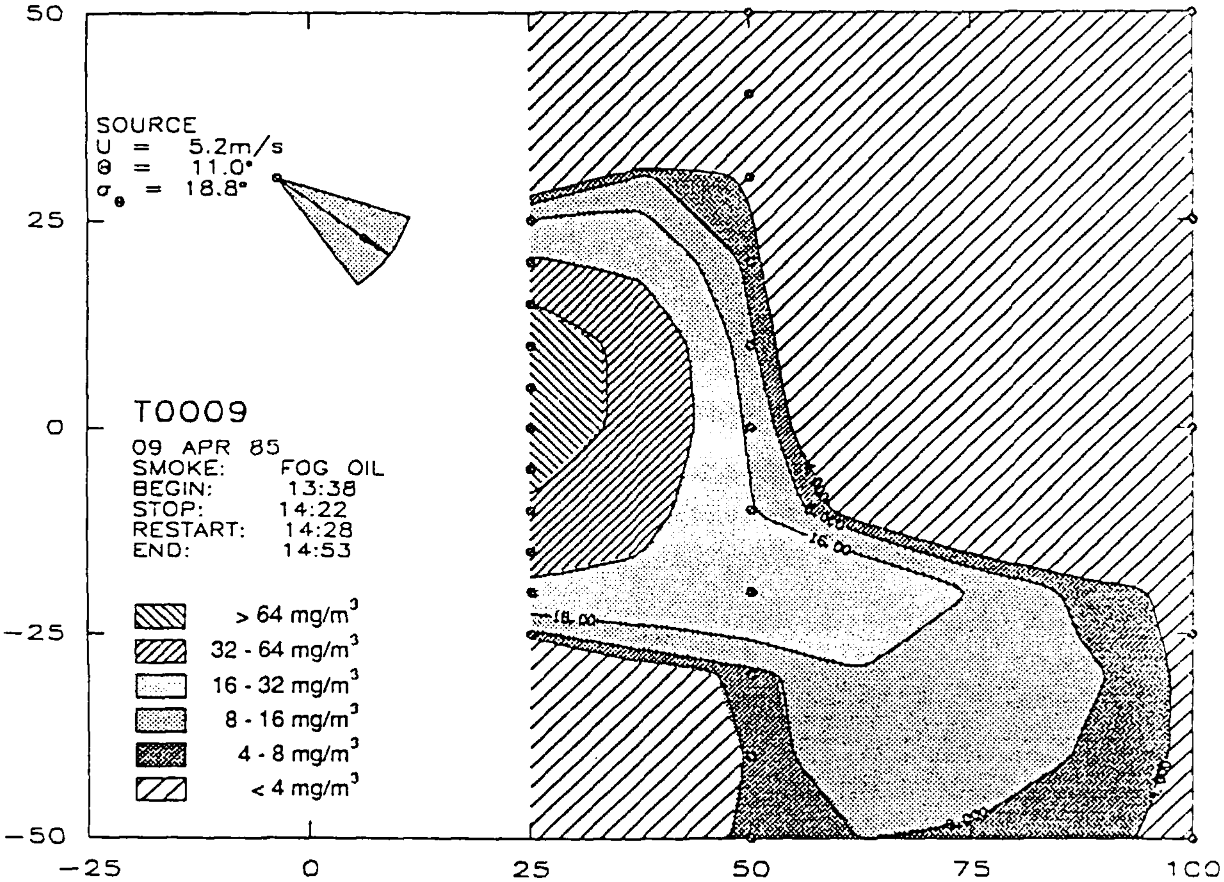


Figure 4.2. Isopleths of average concentration for test T0009 at Dugway Proving Ground. Sampler locations are indicated by small filled circles. The arrow at the source location indicates the mean wind direction; its length is proportional to the mean wind speed. The shaded sector around the arrow indicates the standard deviation of the wind direction.

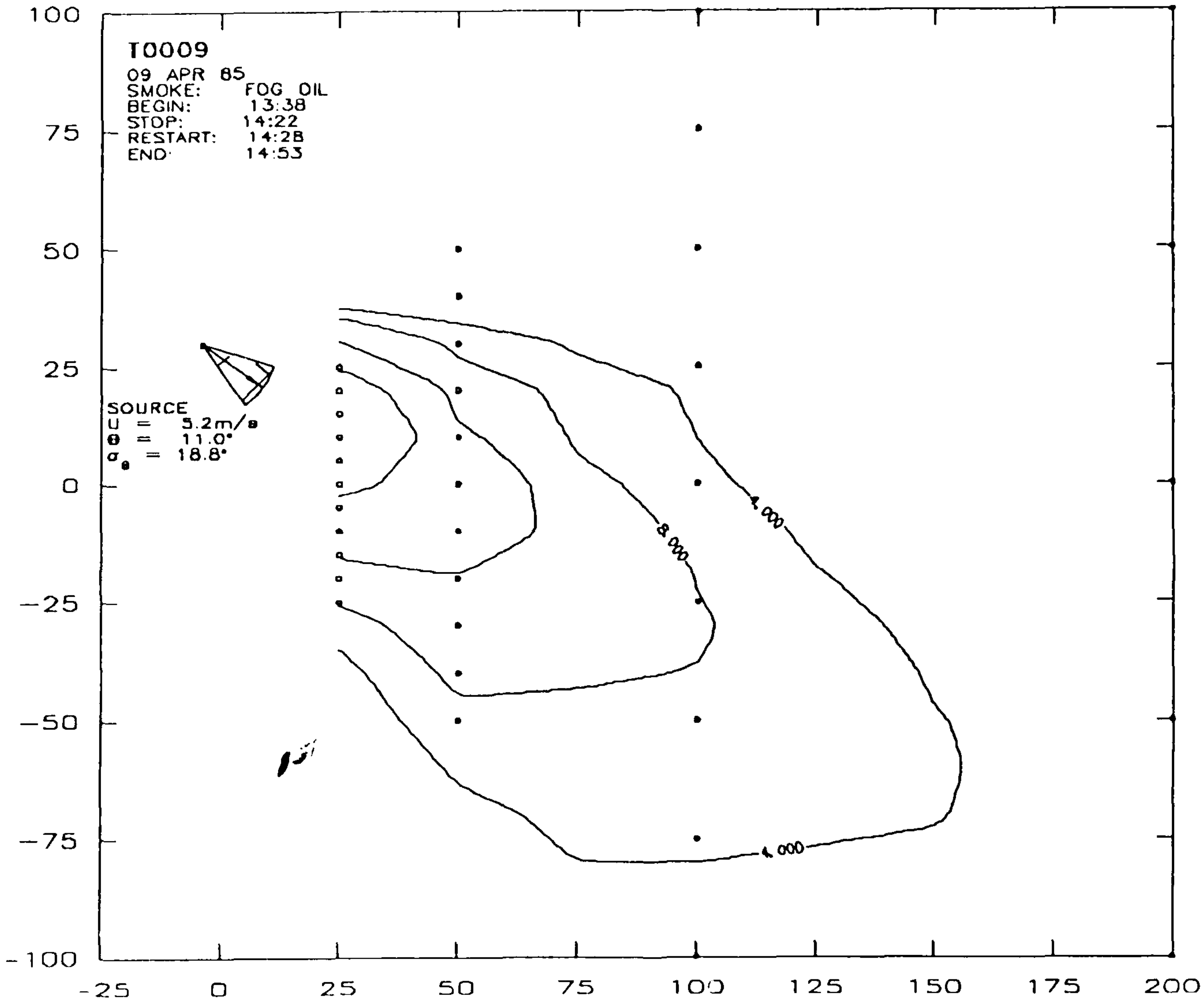


Figure 4.3. Isopleths of average concentration computed on a rectangular grid using the BEAR model for test T0009 at Dugway Proving Ground.

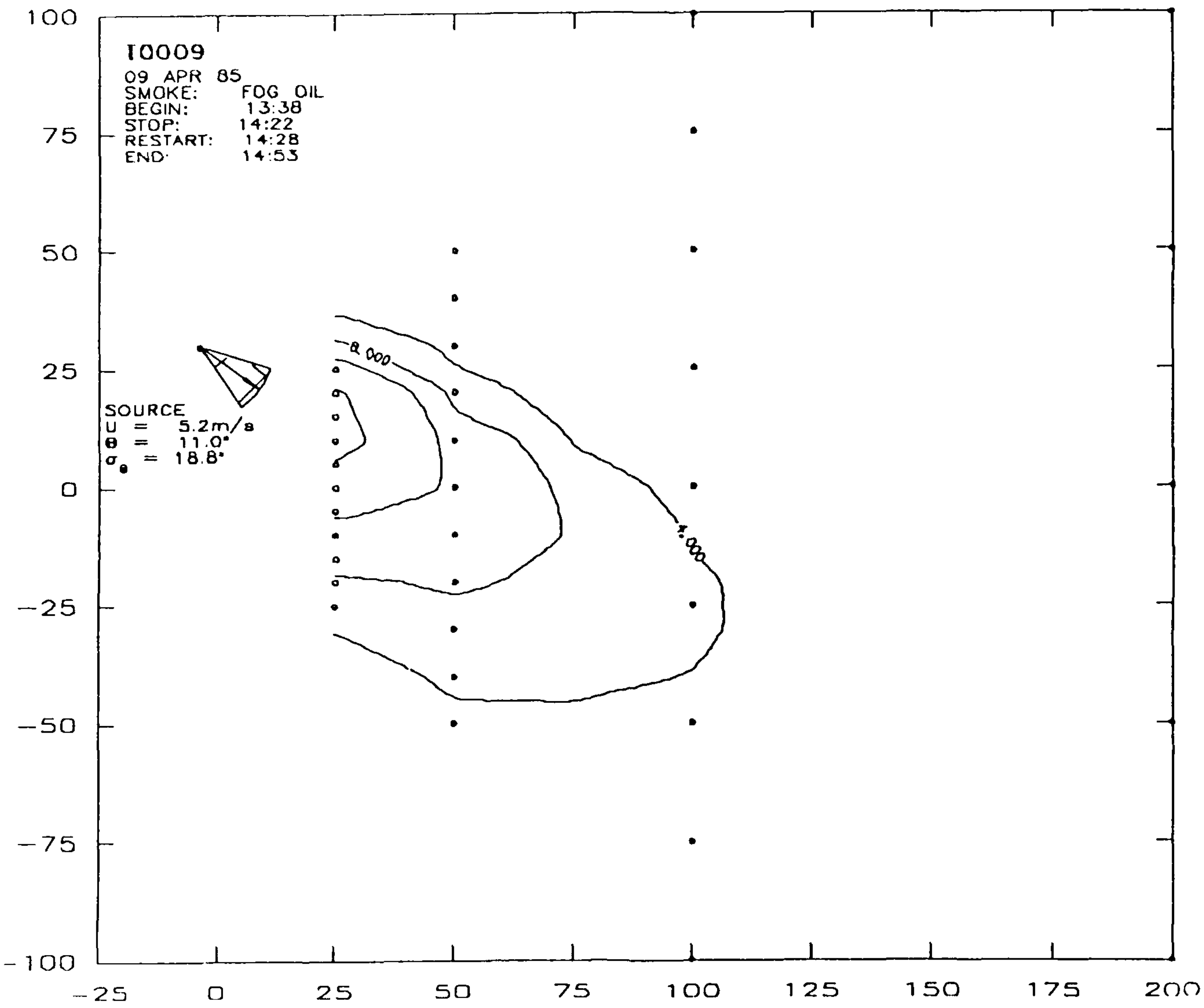


Figure 4.4. Isopleths of average concentration computed on a rectangular grid using the INPUFF-Onsite model for Test T0009 at Dugway Proving Ground.

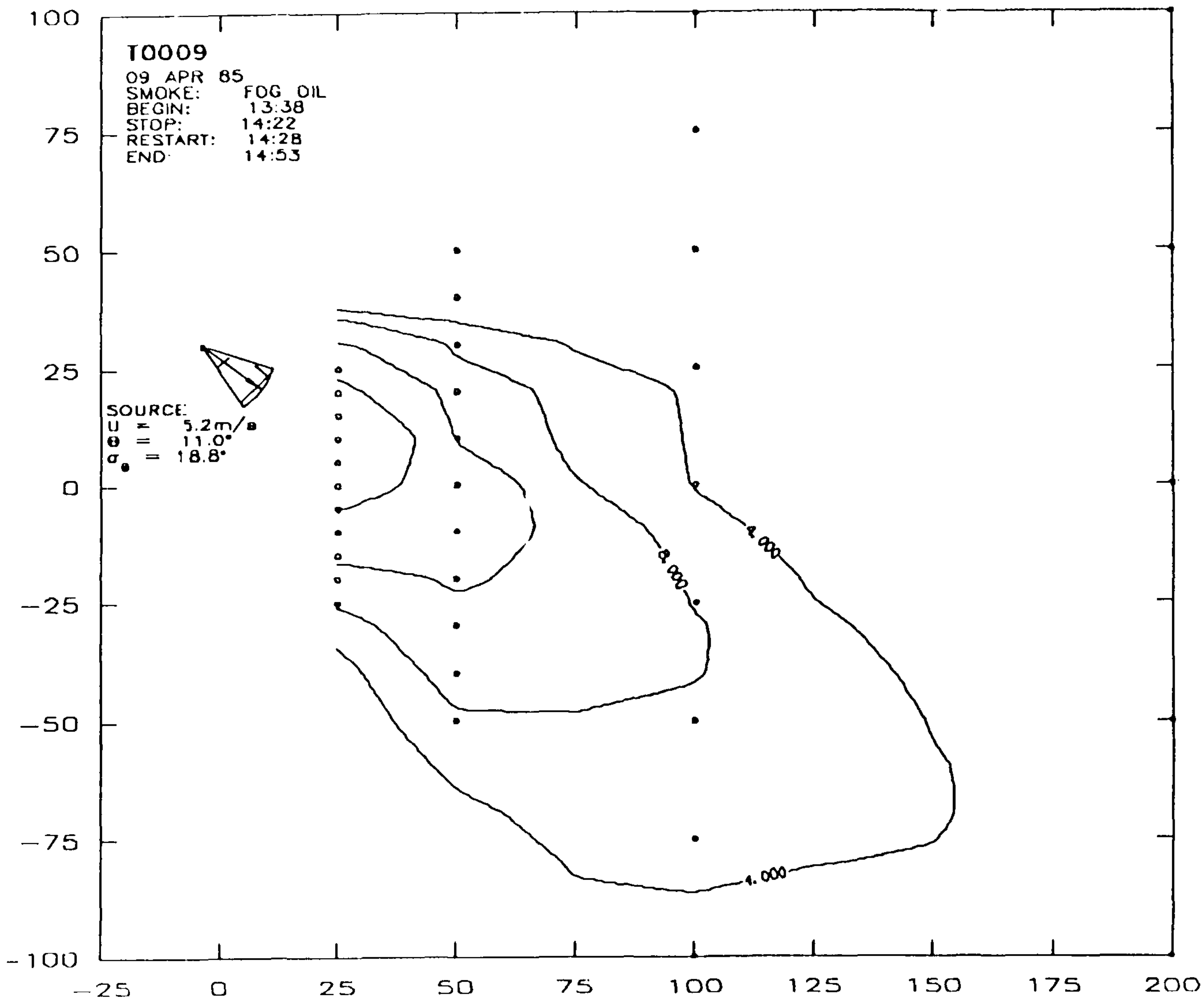


Figure 4.5. Isopleths of average concentration computed on a rectangular grid using the INPUFF-PG model for Test T0009 at Dugway Proving Ground.

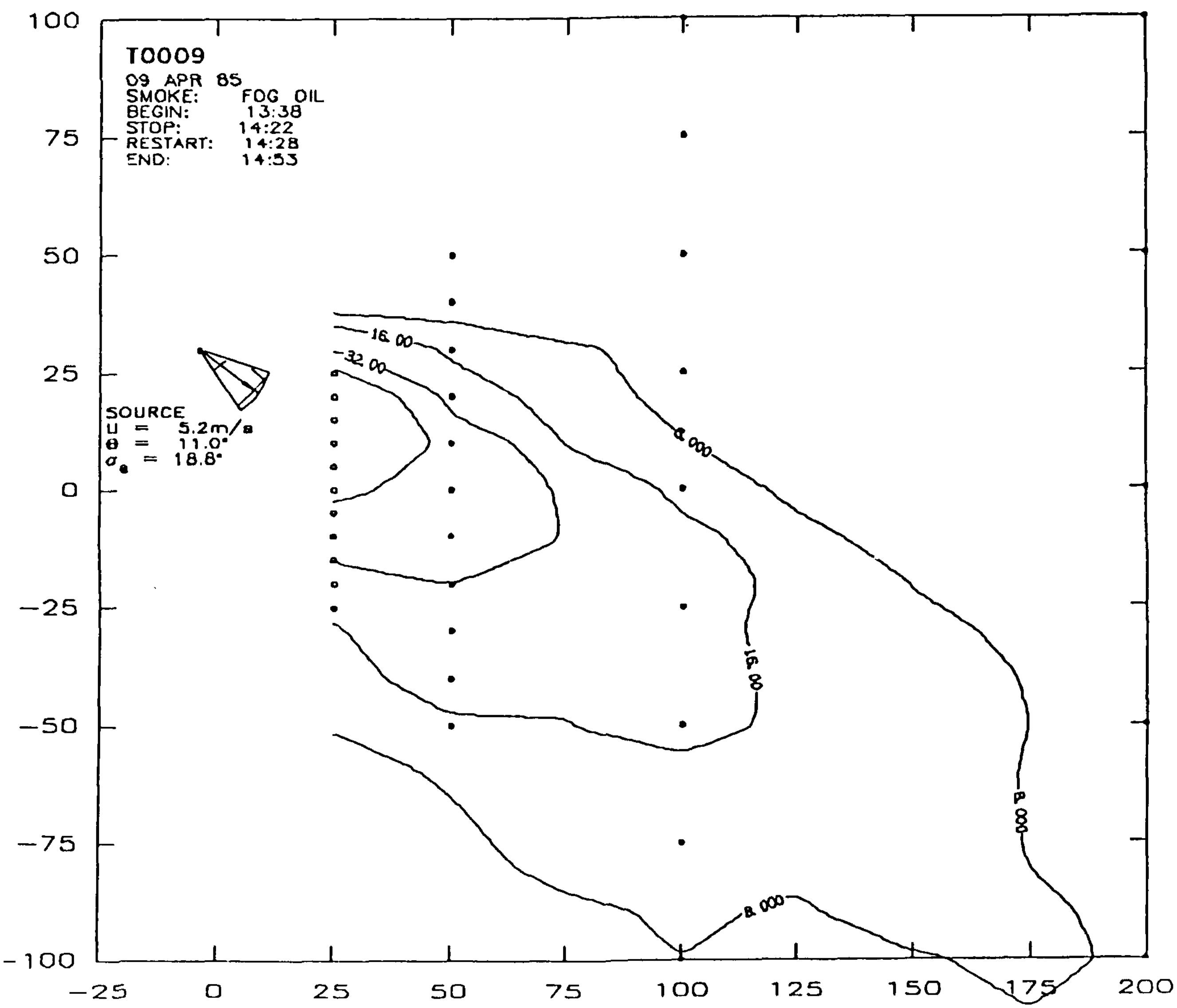


Figure 4.6. Isopleths of average concentration computed on a rectangular grid using the RIMPUFF model for Test T0009 at Dugway Proving Ground.

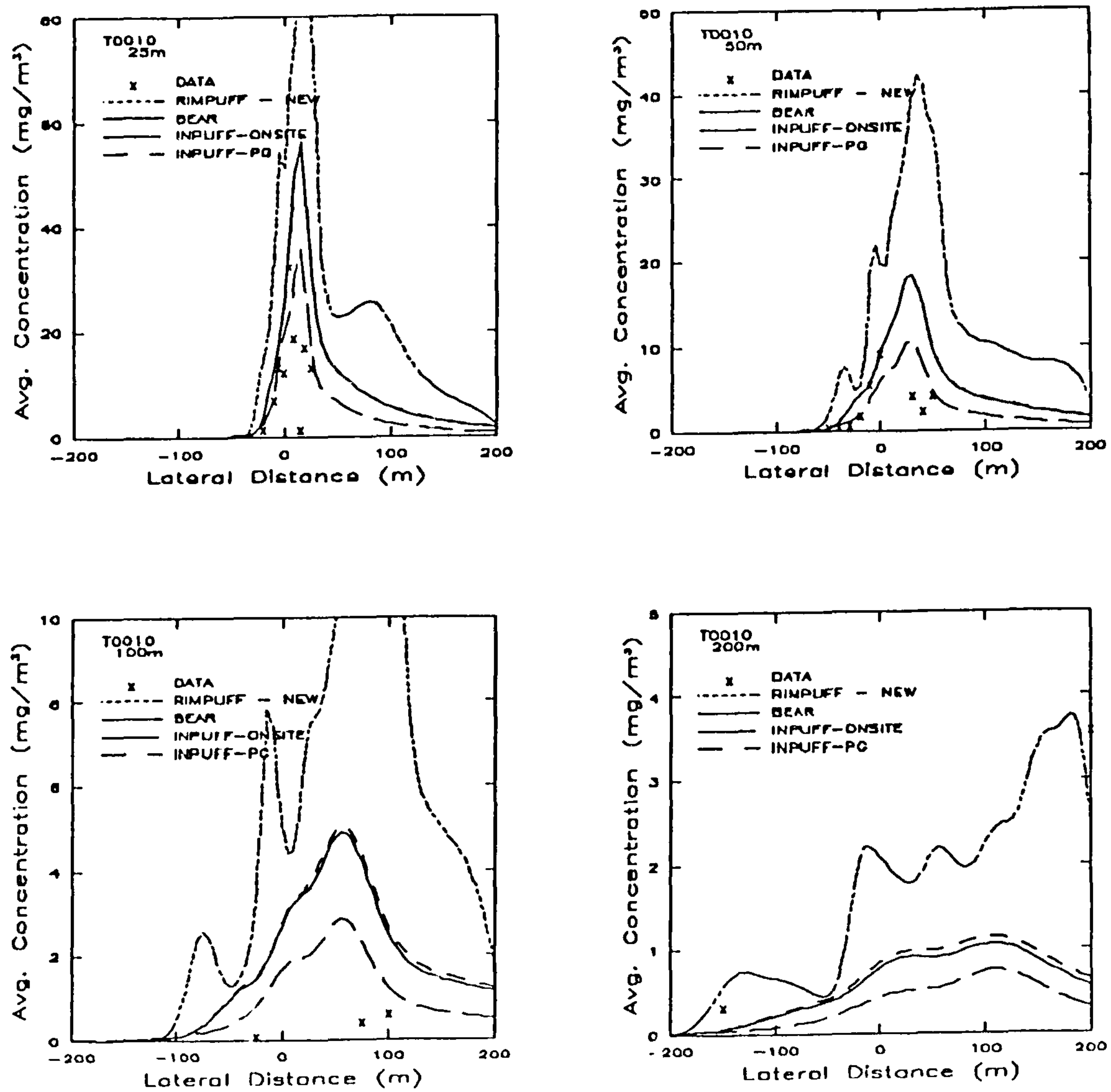


Figure 4.7. Comparison of RIMPUFF, BEAR, INPUFF-Onsite and INPUFF-PG mathematical models with average concentrations from test T0010 at Dugway Proving Ground.

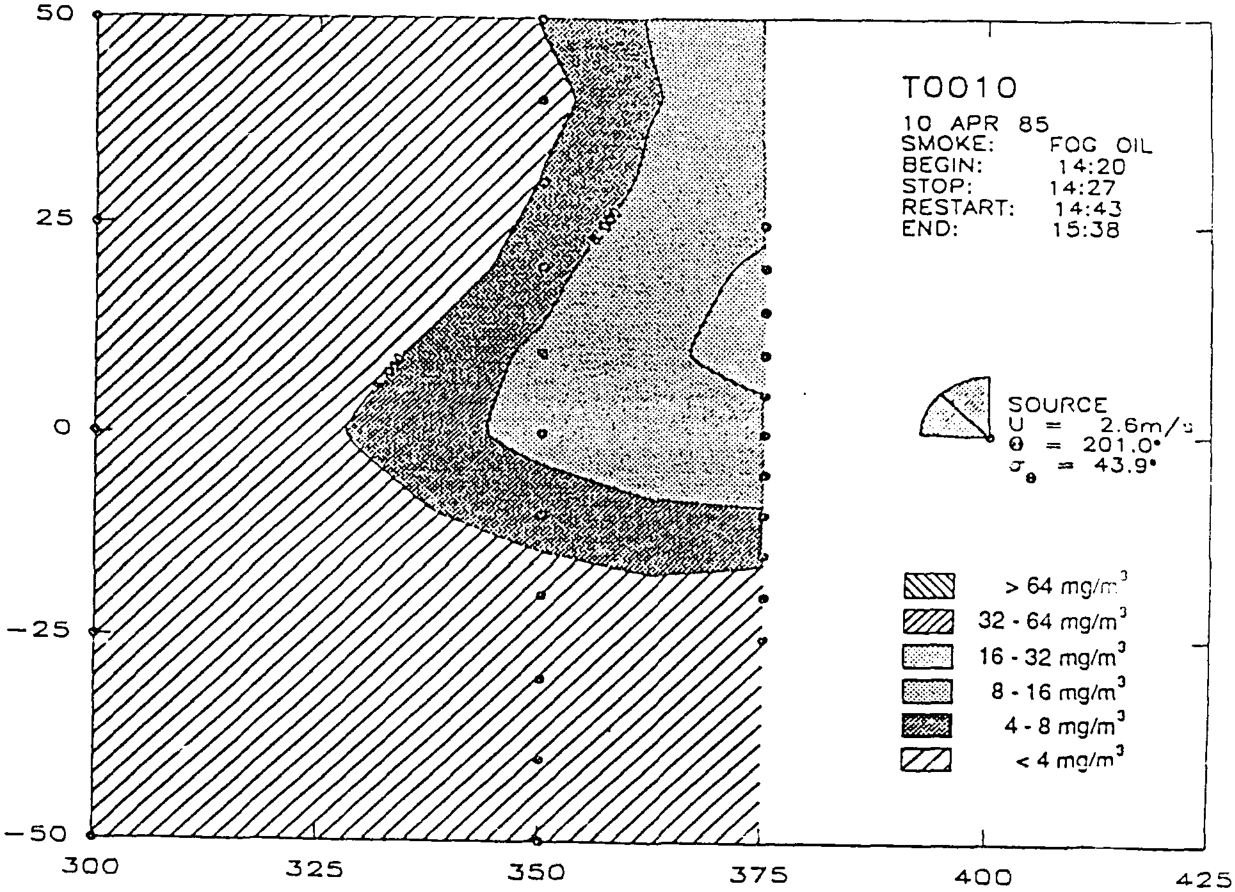


Figure 4.8. Isopleths of average concentration for test T0010 at Dugway Proving Ground. Sampler locations are indicated by small filled circles. The arrow at the source location indicates the mean wind direction; its length is proportional to the mean wind speed. The shaded sector around the arrow indicates the standard deviation of the wind direction.

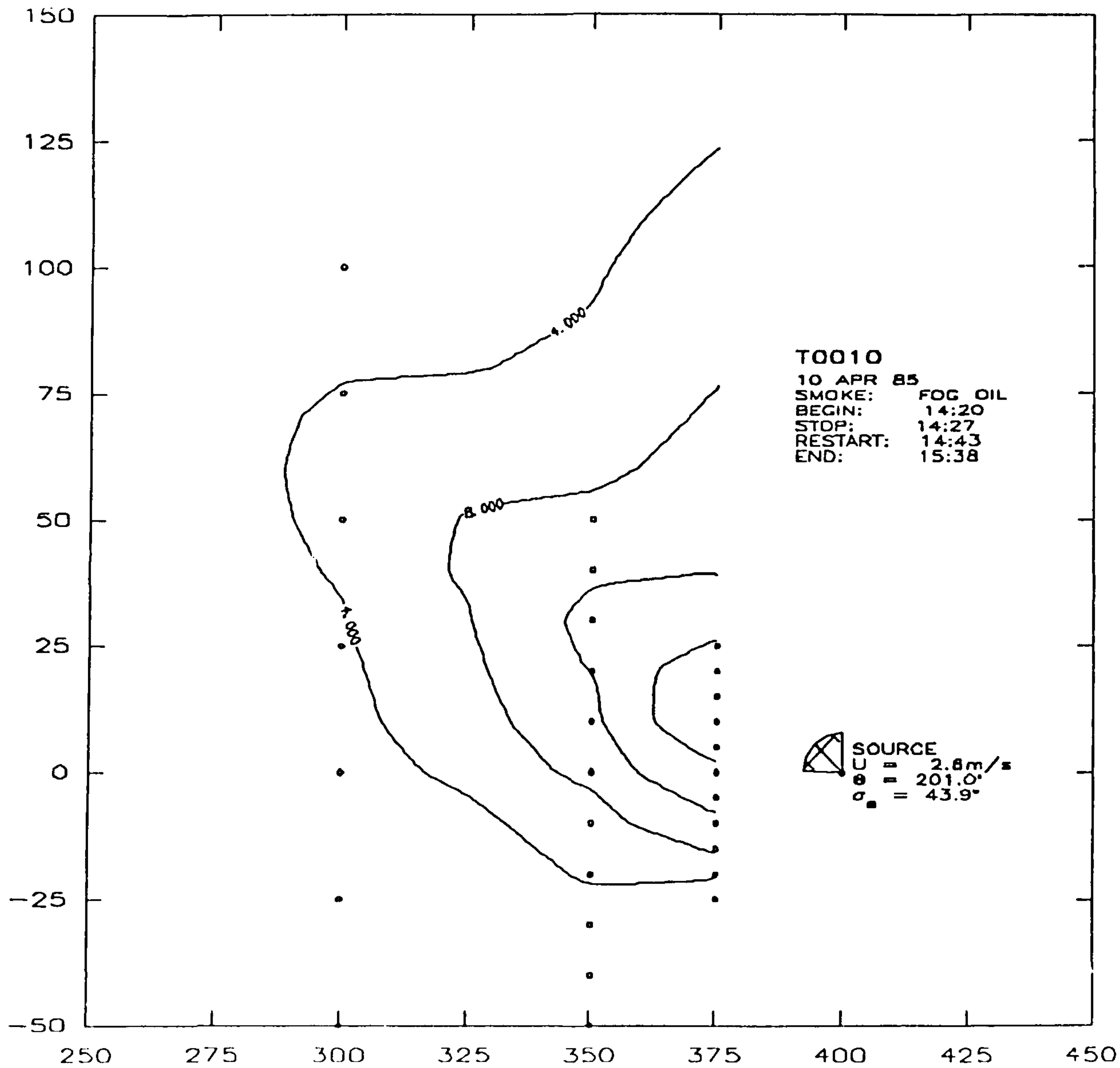


Figure 4.9. Isopleths of average concentration computed on a rectangular grid using the BEAR model for test T0010 at Dugway Proving Ground.

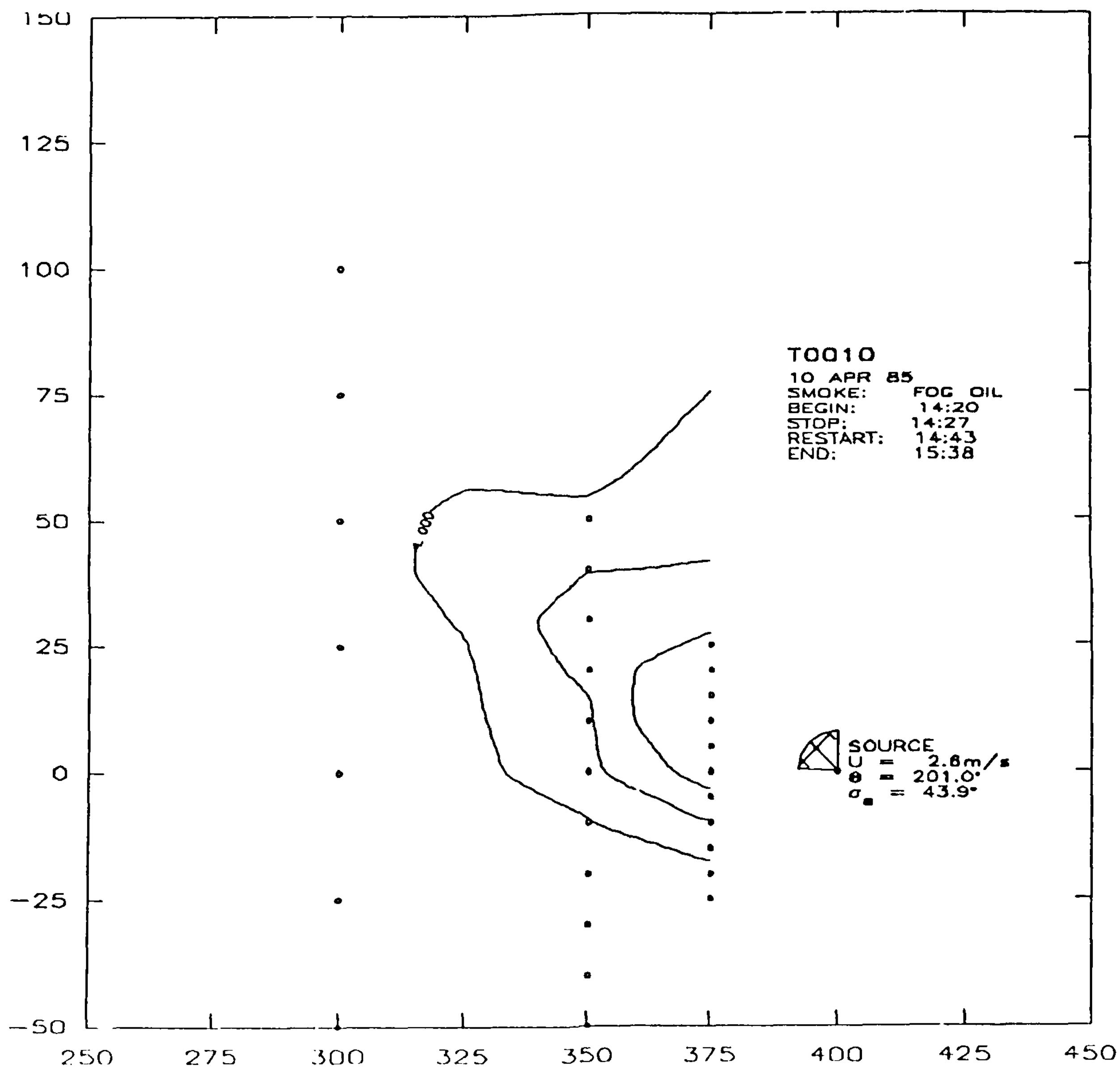


Figure 4.10. Isopleths of average concentration computed on a rectangular grid using the INPUFF-Onsite model for Test T0010 at Dugway Proving Ground.

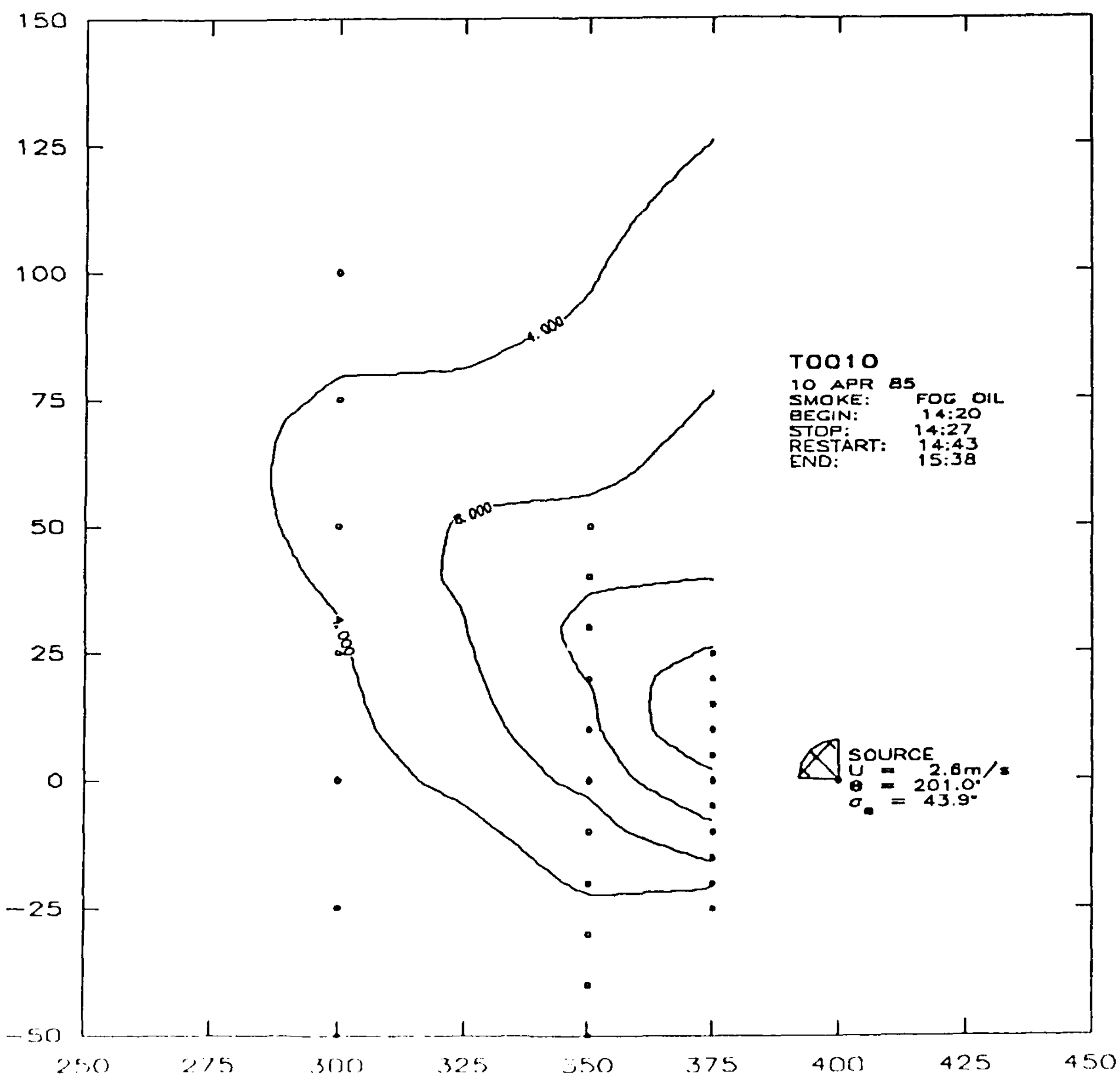


Figure 4.11 Isopleths of average concentration computed on a rectangular grid using the INPUFF-PG model for Test T0010 at Dugway Proving Ground.

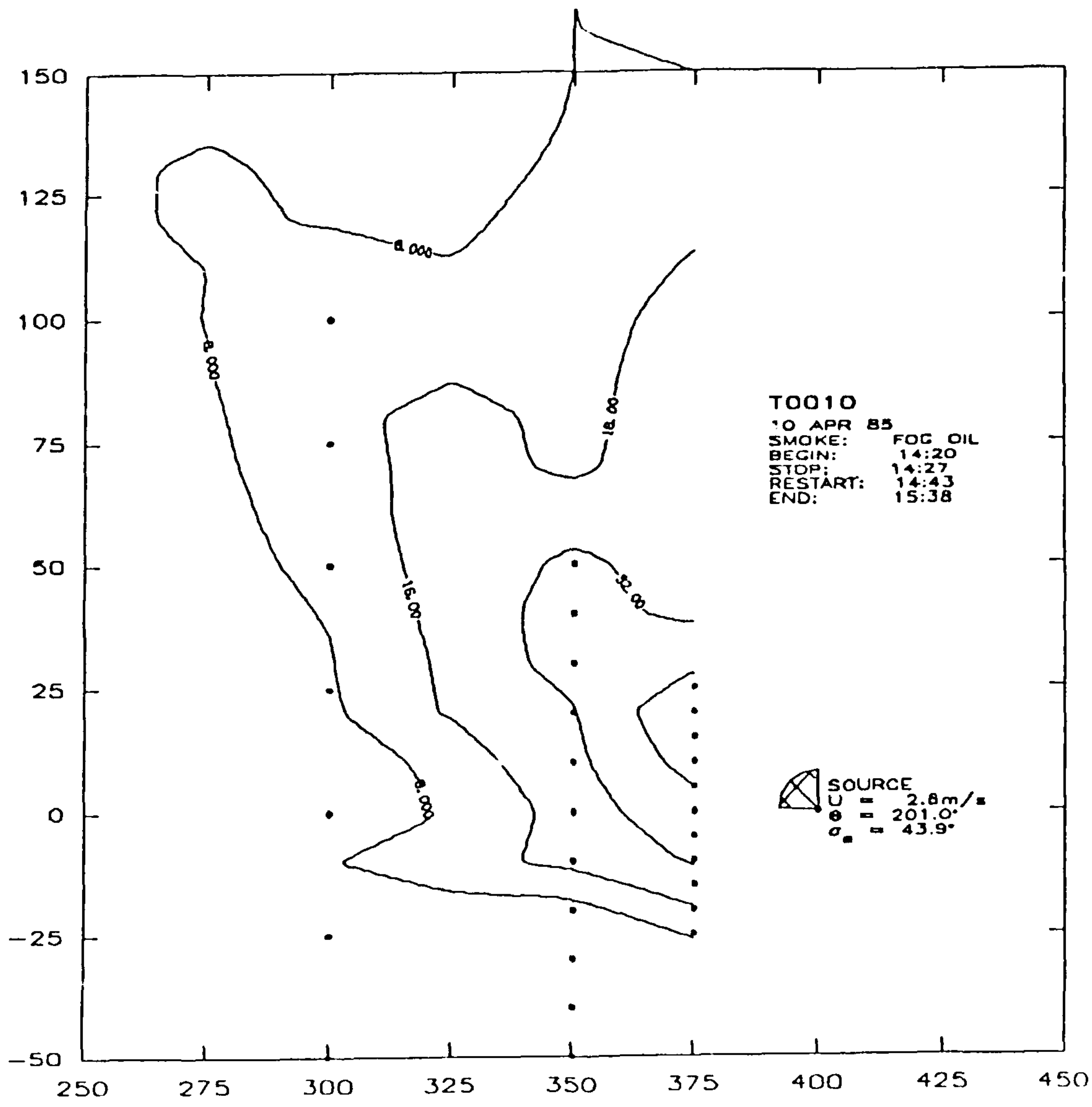


Figure 4.12. Isopleths of average concentration computed on a rectangular grid using the RIMPUFF model for Test T0010 at Dugway Proving Ground.

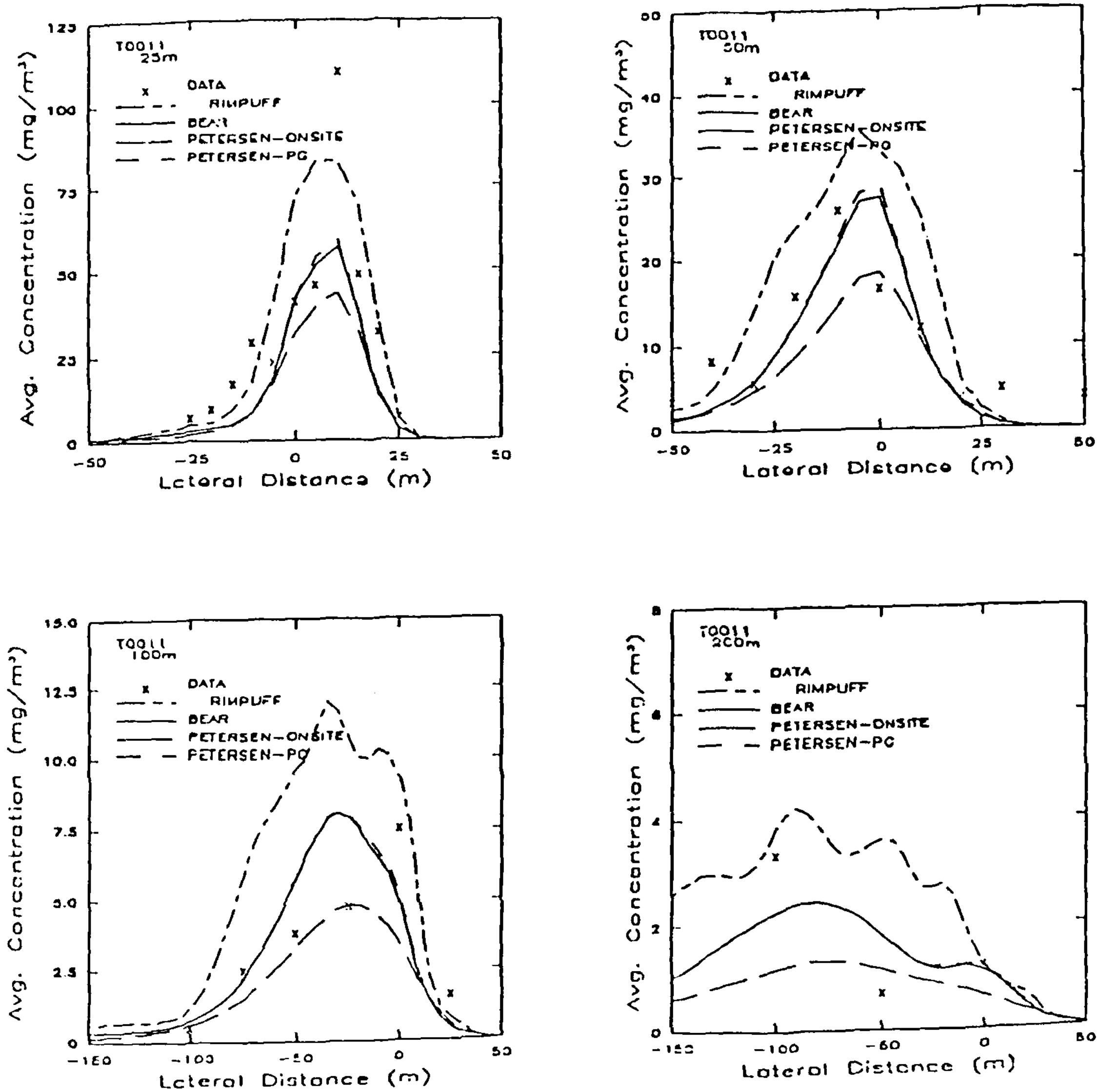


Figure 4.13. Comparison of RIMPUFF, BEAR, INPUFF-Onsite and INPUFF-PG mathematical models with average concentrations from test T0011 at Dugway Proving Ground.

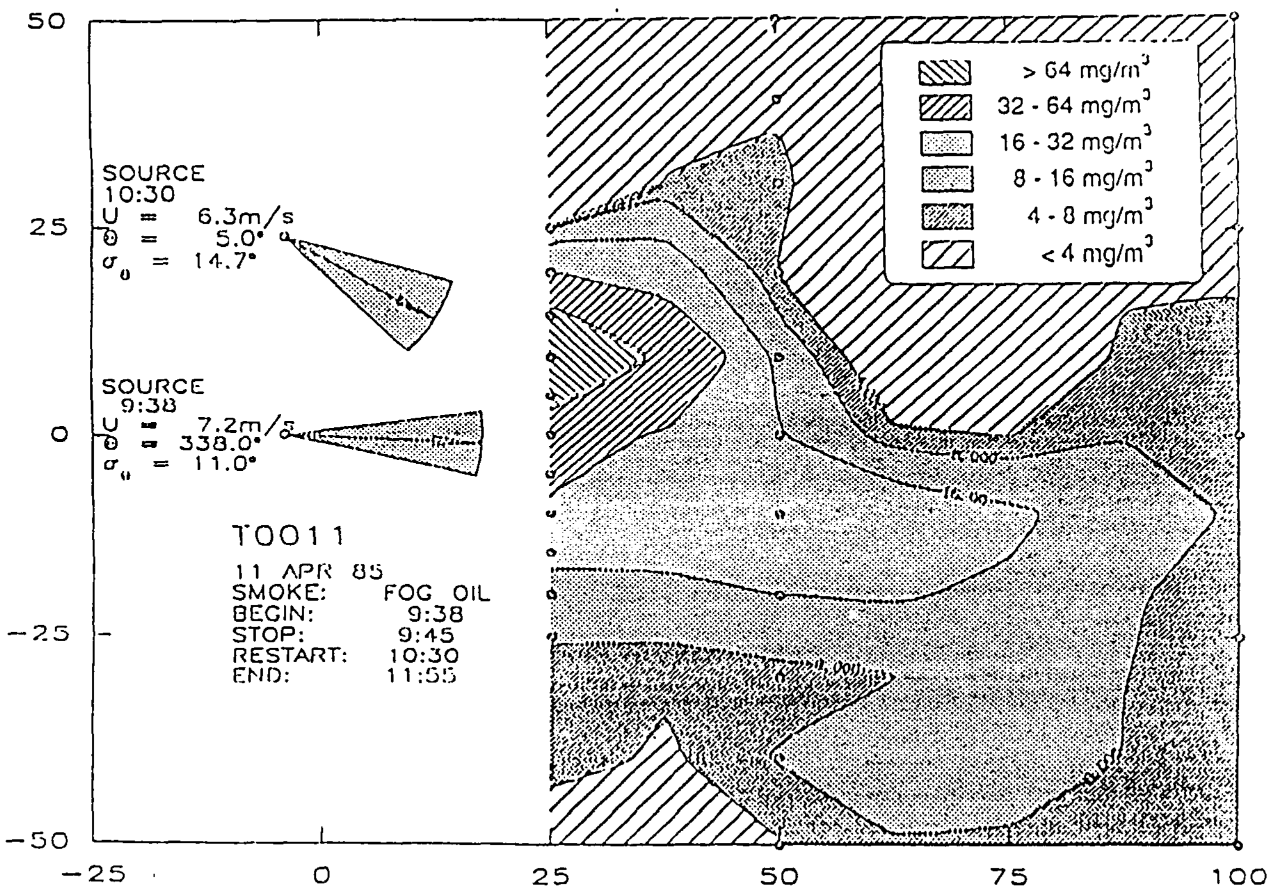


Figure 4.14. Isopleths of average concentration for test T0011 at Dugway Proving Ground. Sampler locations are indicated by small filled circles. The arrow at the source location indicates the mean wind direction; its length is proportional to the mean wind speed. The shaded sector around the arrow indicates the standard deviation of the wind direction.

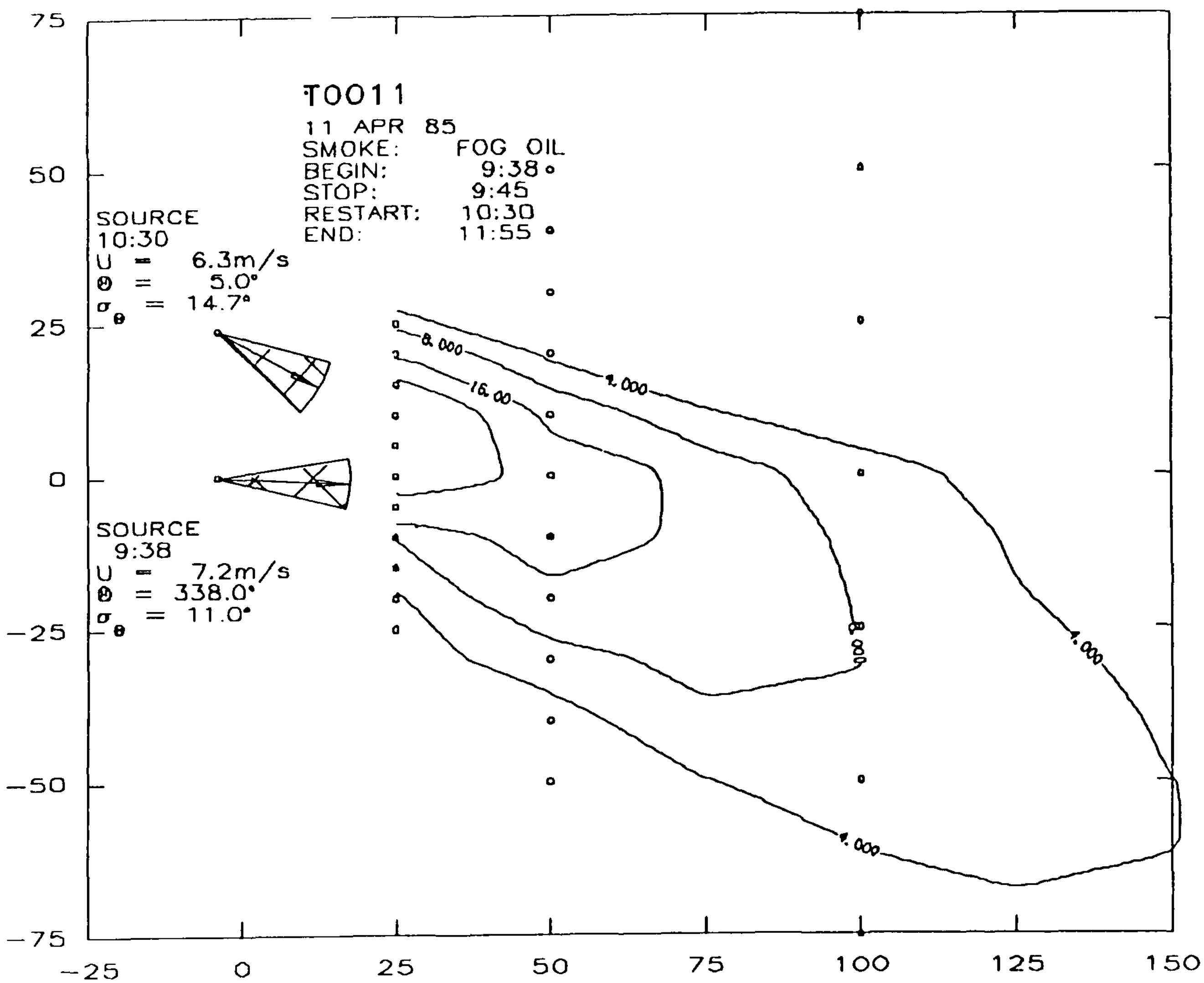


Figure 4.15. Isopleths of average concentration computed on a rectangular grid using the BEAR model for test T0011 at Dugway Proving Ground.

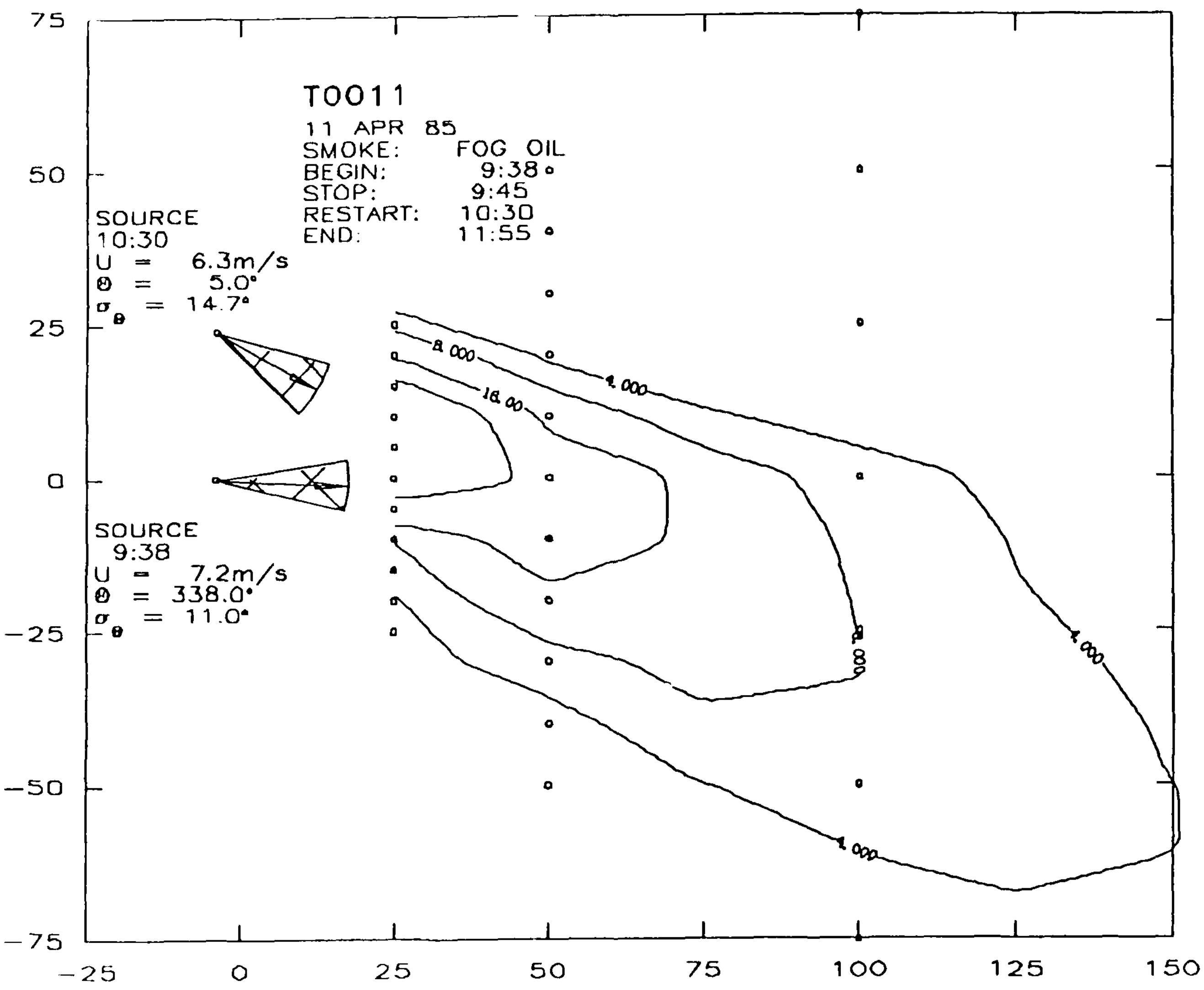


Figure 4.16. Isopleths of average concentration computed on a rectangular grid using the INPUFF-Onsite model for Test T0011 at Dugway Proving Ground.

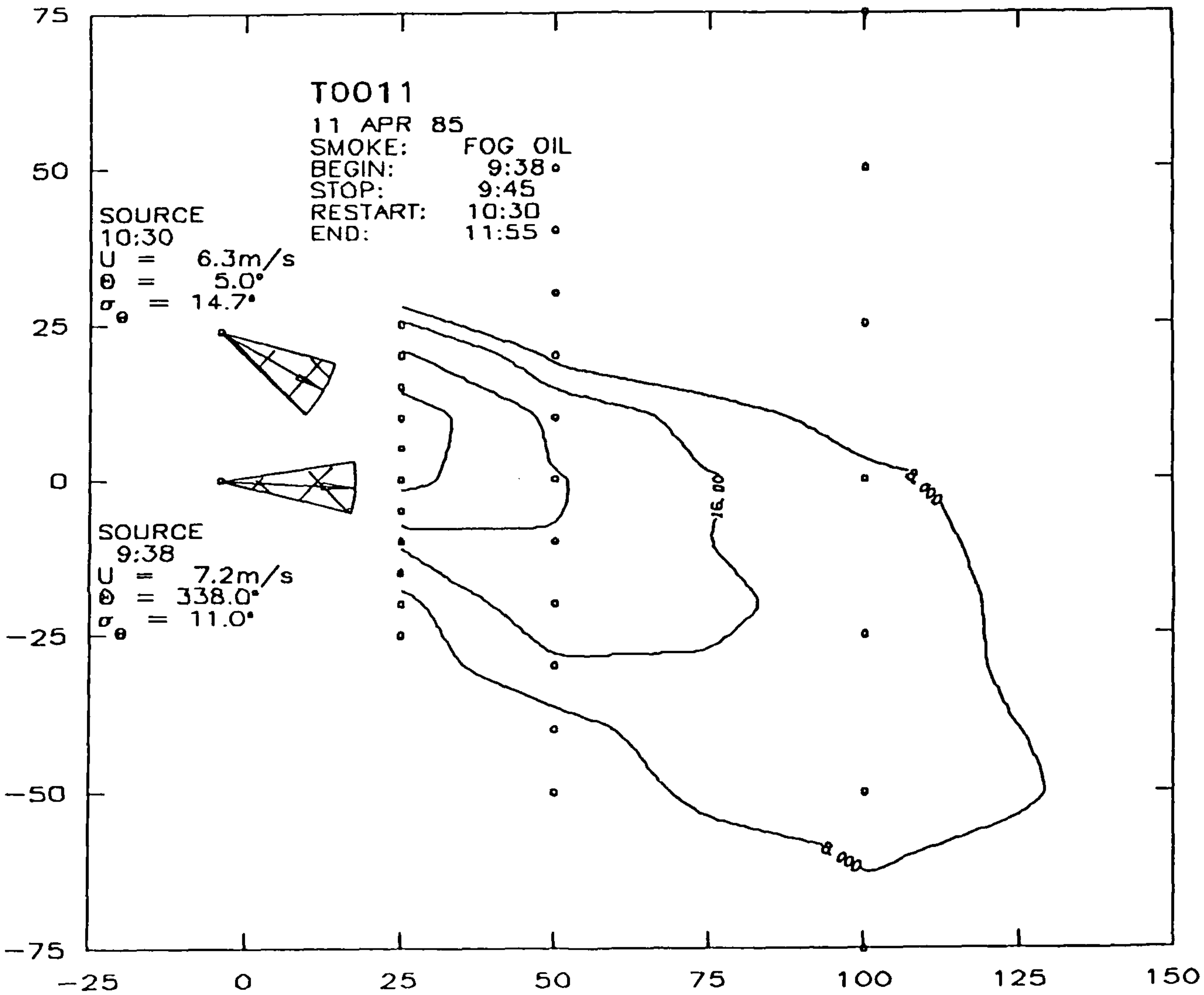


Figure 4.17. Isopleths of average concentration computed on a rectangular grid using the INPUFF-PG model for Test T0011 at Dugway Proving Ground.

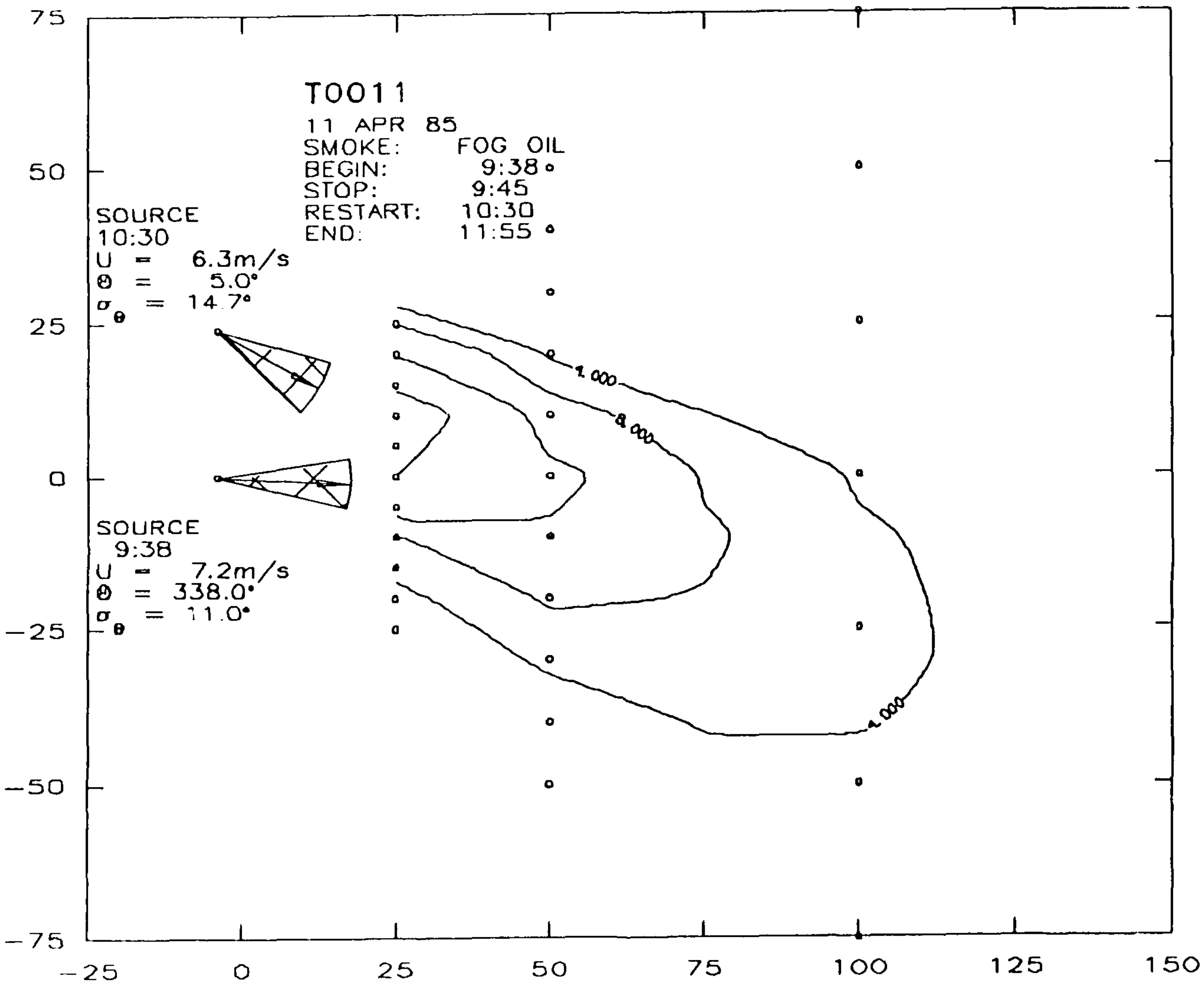


Figure 4.18. Isopleths of average concentration computed on a rectangular grid using the RIMPUFF model for Test T0011 at Dugway Proving Ground.

For INPUFF, two modeling schemes were tested; the On-Site scheme and the P-G scheme. The on-site scheme employs measured turbulence data (σ_θ and σ_ϕ) whereas the P-G scheme requires the input of a Pasquill stability class.

All three field tests were taken under convective conditions with the exception that neutral atmospheric conditions occur for the first part of test T0011 a. Color video photographs recorded a rise of the plume centerline with distance beyond about 300-500 m downwind.

The complete set of model/data comparisons are presented in Figures 4.1 to 4.18. Figures 4.1 to 4.6 refer to model/data comparisons for test T0009. Figures 4.7 to 4.12 refer to model/data comparisons for test T0010. Finally, Figure 4.13 to 4.18 refer to test T0011. In those figures, two types of evaluations are made:

(a) comparisons of average concentrations in mg/m^3 between predicted and observed over the time of the smoke release. Presentations of these pointwise model/data comparisons are made by transect downwind of the source for each experiment, and

(b) comparisons of isocontours of dosage between data and model predictions. Contours are typically prepared for 4, 8, 16, and 32 mg/m^3. The purpose of these contour comparisons is to determine if the spatial pattern of the predicted average smoke concentrations compares well with the observed pattern.

The type (a) comparisons represent only point-by-point evaluations of model predictions. In actuality, the presence of wind-direction errors in the data or the model predictions could lead to inaccurate pointwise comparisons, yet the spatial pattern of the predictions and observations may look alike. For example, the spatial patterns may look alike but be rotated from each other. In such a case, the pointwise comparisons may look poor but the spatial patterns may look similar. In this way, the type (a) and type (b) comparisons complement each other by evaluating the models point-by-point and through their isocontour patterns.

For the input meteorological data, the 10 m height was used to represent the wind data required by the models. This 10 m level for the meteorological data is recommended by the model developers. The smoke release height is at 2.0 m from the ground; therefore, the center of each puff remains at the elevation of release (2.0 m) during its entire downwind dispersion history.

It was observed in the field at Dugway Proving Ground that the plume centerline rises under convective conditions. That observation contradicts the models' assumption that the centerline of the plume remains at the elevation of release (for a nonbuoyant source like the fog oil release). However, the fog oil smoke data were acquired at distances close enough to the generator (within 200m) that the rising centerline phenomenon had not yet had a chance to manifest itself in these data sets. As will be seen later in the Camp Atterbury comparisons, the rising centerline was observed in the data for distances of about 250 - 400 m and beyond under the convective conditions present during that study.

4.1 Discussion of the Field Data for the Dugway Tests

An examination of the average concentration isocontours (Figures 4.1, 4.7, and 4.13) reveals a general consistency among the data presented for tests T0009, T0010, and T0011. The three experiments are similar in terms of generator run time, downwind sampler coverage, and meteorological conditions. As a result, the dosages measured should be similar. Indeed, an examination of Figures 4.1, 4.7 and 4.13 reveal that contours of average concentrations of 4 to 64 mg/m^3 are present in <u>each</u> test for samplers out to 200 m from the source.

Other areas of data consistency are as follows:

(a) The lateral distribution of average concentrations appears to be Gaussian in shape based on an examination of crosswind measurements for each of the transects. The result is consistent with the Gaussian predictions of the models.

(b) Average concentrations decrease in a systematic way in the longitudinal direction. The measured values appear to decline by factors of about 30-90 from the 25 m transect to the 200 m transect. The model predictions decline about the same amount, roughly by factors of 25-70. The decrease in concentrations with distance tends to be in a geometric manner with increasing rates of decline with distance. For example, the centerline distance to 8 mg/m^3 should be greater than twice the centerline distance to the 4 mg/m^3 average concentration value. Since in dispersion theory, σ_y and σ_z increases at a rate faster than linear as a function of x for stability classes B and C, then the resulting concentration computed should decrease more rapidly than linearly. The rate of decrease in both models and data is faster than linear and generally of the same order of magnitude for models and data.

(c) A noticeable meandering of the centerline of the isopleths is observed in tests T0009 and T0011. No such meandering seems to have occurred in test T0010. The distortion is seen to be largely due to interpolation ambiguities and not a fault in the data.

Contours resulting from model predictions are presented in Figures 4.3-4.6,4.9-4.12, and 4.15-4.18. These contours were determined from predictions for a rectangular grid (7 x 11) and do not appear to be in especially close agreement with the data. The general features and order of magnitude of predicted and observed contours appear to be similar, however. Figures 4.1,4.7, and 4.13 present model/data comparisons at the actual sampler locations. Those figures generally reveal a fair representation of the data. Some distortion cannot be avoided as a result of interpolation ambiguities (especially on an irregular grid) and not a fault of the data themselves.

4.2. Discussion of the Model/Data Comparisons for the Dugway Tests

4. 2 .1 Test T0009

For this test, the source was initially located at J4 (0,0) rather than (-4,30) as indicated in the data figure. However, because the bulk of the plume missed the sampling grid to the west (toward the bottom of the figure) from this release point, the source was relocated to (-4,30) within the first 15 minutes of the test. Because the smoke release continued during the relocation, the data closest to the release point appears to suggest a release point between (0,0) and (-4,30).

Given this complication, one may make the following conclusions from examining Figures 4.1 to 4.6:

(a) Agreement between models and data are qualitatively good,

(b) Model predictions are generally within a factor of 3 of the data. The average concentration data have larger values than the model predictions for the 25 m transect, but become in closer agreement with the model predictions for the further transects 50-200 m.

(c) As can best be seen with the limited data available (especially at the further transects), the lateral spreading of the plume seems to be reasonably well predicted by the models.

(d) In terms of contour shapes and magnitudes, the models seem to be in reasonable agreement with the data. The RIMPUFF model predicts irregular looking contours perhaps because of the very short meteorological time step used in that model and thus the many different directions the time-dependent puff releases follow during the experiment.

4. 2 .2 Test T0010

The wind direction frequency was found to be bimodal for this test whereas the wind direction frequency distribution for tests T0009 and T0011 were both nearly normal. A model that accounts for time-dependent variations in wind direction is really needed in this case because a single average wind direction does not fully represent the distribution in wind directions over the test period.

The following conclusions may be drawn from the examination of Figures 4.7 to 4.12:

(a) Model predictions are within a factor-of-2 (model predictions are larger) of the data for the 25 m and 50 m transects. However, model predictions are significantly higher than the data for the 100 m and 200 m transects. A careful examination of the frequency distribution and the contour plots for T0010 shows that the data does reflect the observed wind pattern. The plume passing off the sampling grid makes it difficult to evaluate the cause of the discrepancies at the 100 m and 200 m arc.

(b) Lateral spreading appears to be consistent between the models and data -- given the limited data available on the 100 m and 200 m transects.

(c) Concentration maxima are at approximately the correct location on the 25 and 50 m transects. No evaluation can be made for the 100 and 200m transects due to lack of a refined grid of data values, and

(d) The predicted average concentration contours are good representations of the data contour with the RIMPUFF model providing puffs that are more expansive laterally and longitudinally as compared with the data.

4.2.3 Test T0011

During this test, the wind direction changed while the generators were being field-repaired. To accommodate this wind shift, the generator was relocated prior to restarting the test. Both locations are indicated in Figure 4.14. Conclusions from the model/data comparisons for test T0011 are as follows:

(a) Model predictions are excellent for this case both in terms of peak concentration value at each transect and lateral spreading at each transect. Model predictions are within a factor-of-2 of the data at each transect,

(b) Movement of the plume off the grid at the 200 m transect prevents a detailed comparison at the distance,

(c) All model predicted contours provide reasonable representations of the data with the model predictions showing less meandering than the data. However, the distortion in the data contour may be largely due to the attempt to interpolate data values on an irregular and somewhat sparse grid.

4.3 Concluding Remarks -- Dugway Tests

One may conclude from examination of the model/data comparisons that, for all nonzero data values and all the models combined, the model predictions give 50% within a factor of two and 70% within a factor of three of the data The Dugway field studies data base does not contain a large enough set of data for a definitive evaluation of models under flat terrain conditions. In addition, data were collected only under unstable meteorological conditions and short distances downwind (up to 200 m). No data for neutral (except for the first part of test T0011) or stable meteorological conditions were obtained.

The performance of each of the models (under these unstable conditions and short downwind distances) appeared to be quite reasonable, however, considering the simplicity of the theories and the limited data required for model input.

The presence of a rising centerline observed beyond about 200 m provides a unique challenge to the models, but that phenomenon was not measured quantitatively in terms of average concentrations during the Dugway tests. The rising centerline phenomenon was observed and quantified as part of the Camp Atterbury tests and the performance of the models is presented later.

A final comparison of the Dugway average concentration data and the model predictions are given in Figure 4.19. This figure is actually a combined plot of results presented in Figures 4.1, 4.7, and 4.13. A 45 degree line on the plot (not shown) would indicate perfect agreement between predictions and observations. The two factor-of-2 lines represent predictions that are a factor of two greater or less than the observed value. The two factor-of-3 lines on the plot represent predictions that are a factor of three greater or less than the observed value. Note the large number of points within the factor-of-3 envelope. Points on one axis or the other indicate spatial offset between the observed and predicted plumes (i.e.,

Figure 4.19A

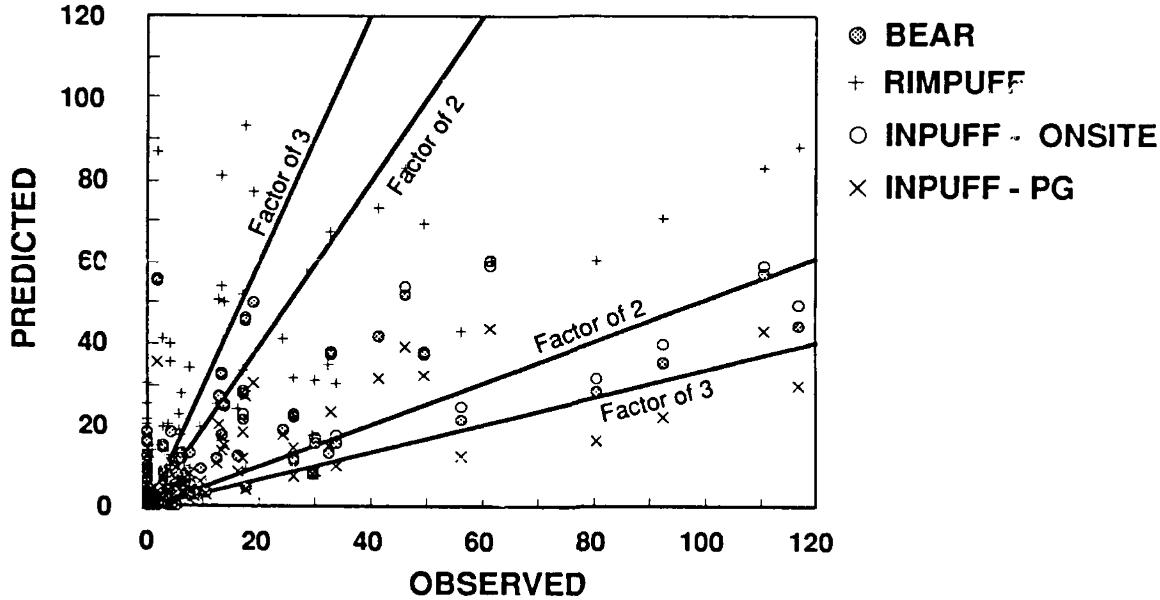


Figure 4.19B

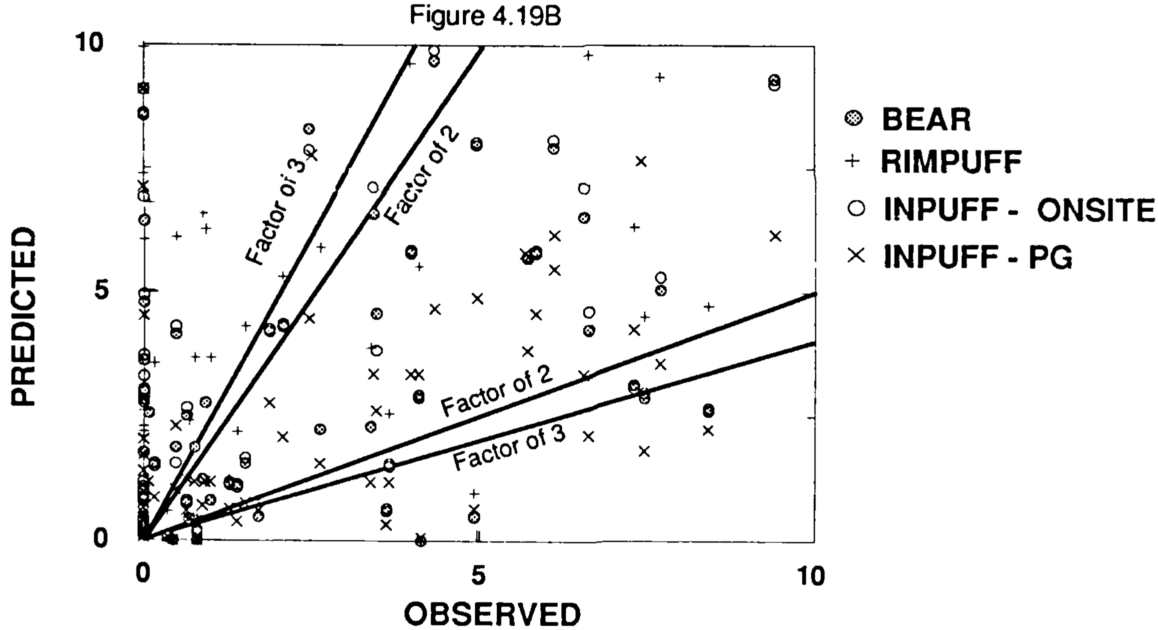


Figure 4.19 Scatterplot comparison of predicted and observed average concentrations for all four models to field data acquired for all three Dugway field tests.

the prediction is zero and the associated observation is nonzero or vice-versa). The typical range of precision believed representative of Gaussian model evaluations is a factor of two for 50% of the time. It is now said for the first time that the particulate phase of the fog oil plume (for these short distances and stability classes B, C, and D) can be represented by the Gaussian dispersion model.

5.0 THE CAMP ATTERBURY FIELD STUDIES

This section provides a short summary of the data acquired in the October / November 1987 field tests at Camp Atterbury (Liljegren et al., 1989). Four data sets are used for model testing in the next section. More detail concerning all the data acquired as well as the equipment and methodology used is given in a data report by Liljegren (Liljegren et al., 1989).

5.1 The Site and the Sampling Layout

A field study on fog-oil dispersion was carried out over a five-week period in October and November 1987 at the Atterbury Reserve Forces Training Center (ARFTC) near Columbus, Indiana. The test site was located in area 7A in the ARFTC complex. The topography of the site and surrounding terrain are presented in Fig. 5.1. The site is positioned in a meadow among low hills which rise approximately 50 m above the mean site elevation of 218 m above mean sea level. The meadow was covered primarily with grass about 1 m high. The lower portions of the site, where water collected after a rainstorm, were covered with briars, brambles and reeds 1 to 2 m high in addition to grass. The surrounding hills were densely wooded with deciduous trees approximately 20 m high. Prior to the testing period, which spanned the first two weeks of November, the trees had dropped most of their leaves.

The sampling network used at Camp Atterbury is illustrated schematically in Fig. 5.2. The filled circles indicate the positions of the masts supporting the concentration samplers. The network was composed of 50 sampling locations on five linear transects oriented perpendicular to the anticipated prevailing wind direction (225 deg east of north). In order to resolve any near-ground concentration gradients, concentration samplers were deployed at elevations of 1,2,4 and 8 m on the first four transects and at elevations of 2 and 8 m on Transect 5 for a total of 192 samplers per test. The transects were arranged at distances of 50, 100, 250,450 and 675 m from the baseline. The fifth transect was located 10 to 25 m upwind of a dense line of trees separating Area 7A and Area 1A. Because the plume was expected to spread linearly as it traveled downwind from the source, the sampler spacing increased on each transect in order to maintain approximately constant lateral resolution. The samplers were spaced at intervals of 15.2,30.4,45.7,61.0, and 122 m respectively on transects 1 to 5.

A number of possible source locations were laid out depending upon wind direction. Real-time plume model predictions made with a computer in the field were used to locate the source for each test depending upon wind direction and the orientation of sampling transects. In this way, efforts were made to have the plume from each test cover as much of the sampling grid as possible. The location of the source and prevailing wind direction for the four fog-oil tests are presented in Fig. 5.3a and 5.3b. The tests are designated by the date and test number on that date. For example, the third fog oil test, designated 1104872, was the second test executed on November 4, 1987.

No on-site meteorological data were available, and the closest National Weather Service Station is in Indianapolis, Indiana. Other than assisting in the determination of the possible best times during the day for a field test, such off-site data was of little use considering that on-site meteorological data from a 10 m tower was acquired at the site for each of the experiments.

5.2. Data on the Fog-Oil Smoke Source

A M3A4 military smoke generator was used to produce the smoke by vaporizing fog oil and ejecting it into the atmosphere at a nominal rate of 46 g/s according to the M3A4 Operator's Manual. The resulting aerosol, as with the M3A3E3 smoke generator, is a two-phase mixture of droplets and vapor. The operation of a single M3A4 smoke generator from a release height of 2 m provides a close approximation to a continuous, ground-level source of varying emission rate with time. Averages of the fog oil source data are presented in Table 5.1. During test 1103871 the power supply for the portable computer used to

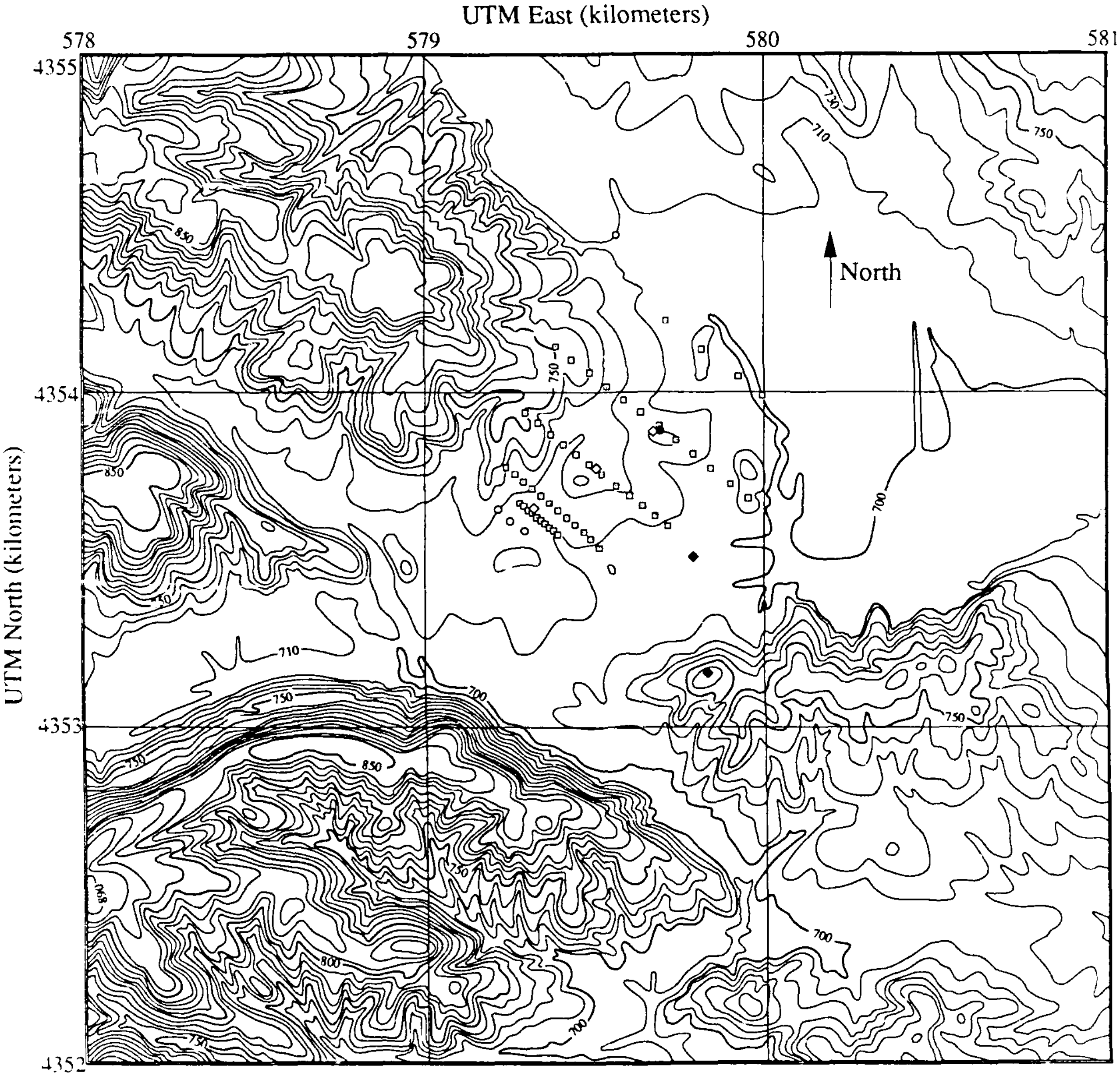


Figure 5.1 Topological Map of the Camp Atterbury Dispersion Site. Elevations are in feet above sea level with isopleths in increments of 10 feet. The horizontal grid is in Universal Transverse Mercator coordinates, with marked increments of 1 kilometer. Sampling mast locations are indicated with filled squares[▫]. Circles [◦] indicate the various release points. Particle size measurements were carried out at the locations marked by diamonds[◇]. The location of the 10 m meteorological instrument tower is indicated by the filled circle[•]. The locations of the 2 m wind monitoring stations operated prior to the dispersion tests for the purpose of assessing the micrometeorology of the site are indicated by the filled diamond[◆].

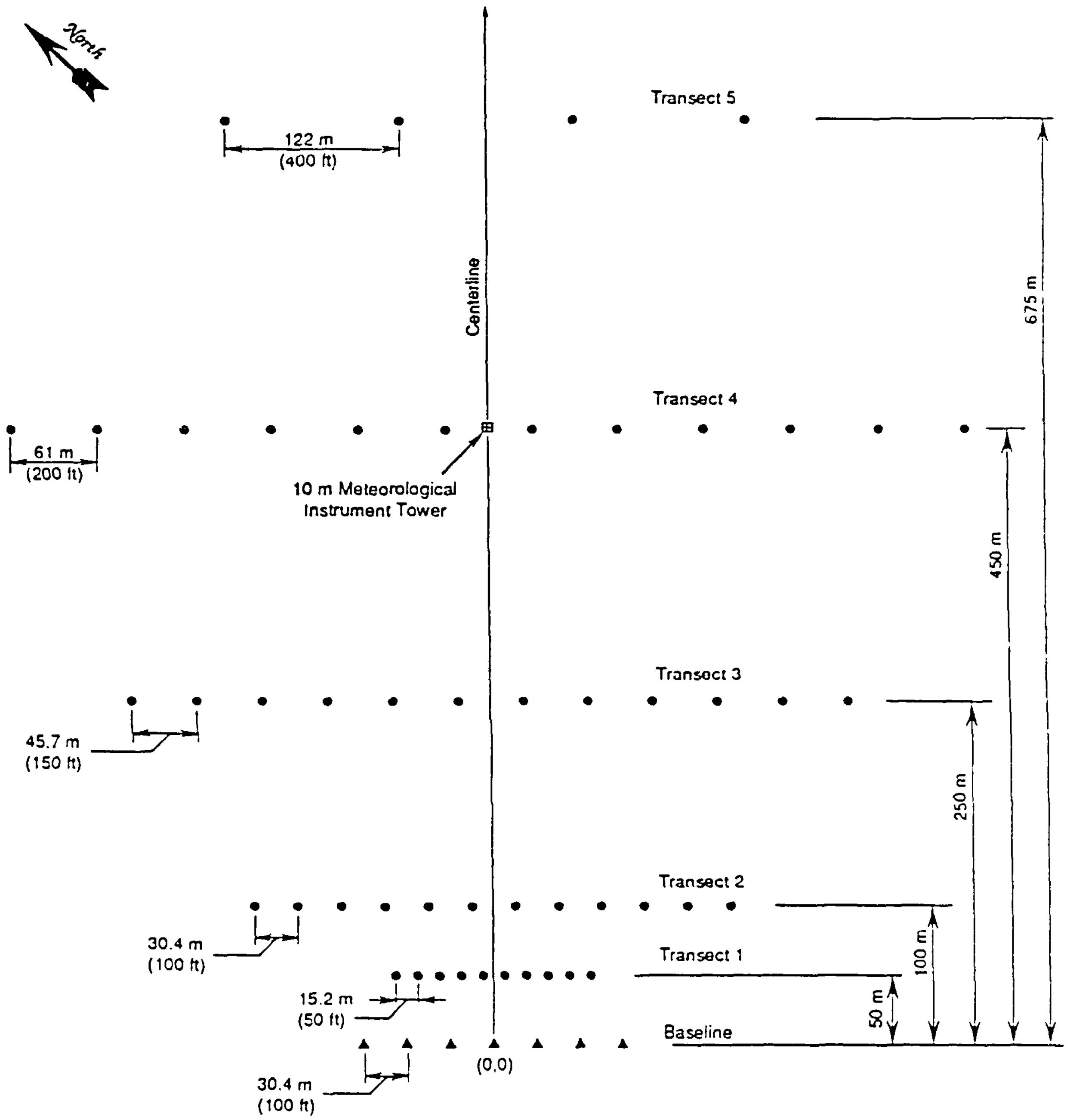


Figure 5.2 Nominal sampling network for Atterbury 87 dispersion field study Symbols are the same as for Fig. 5.1.

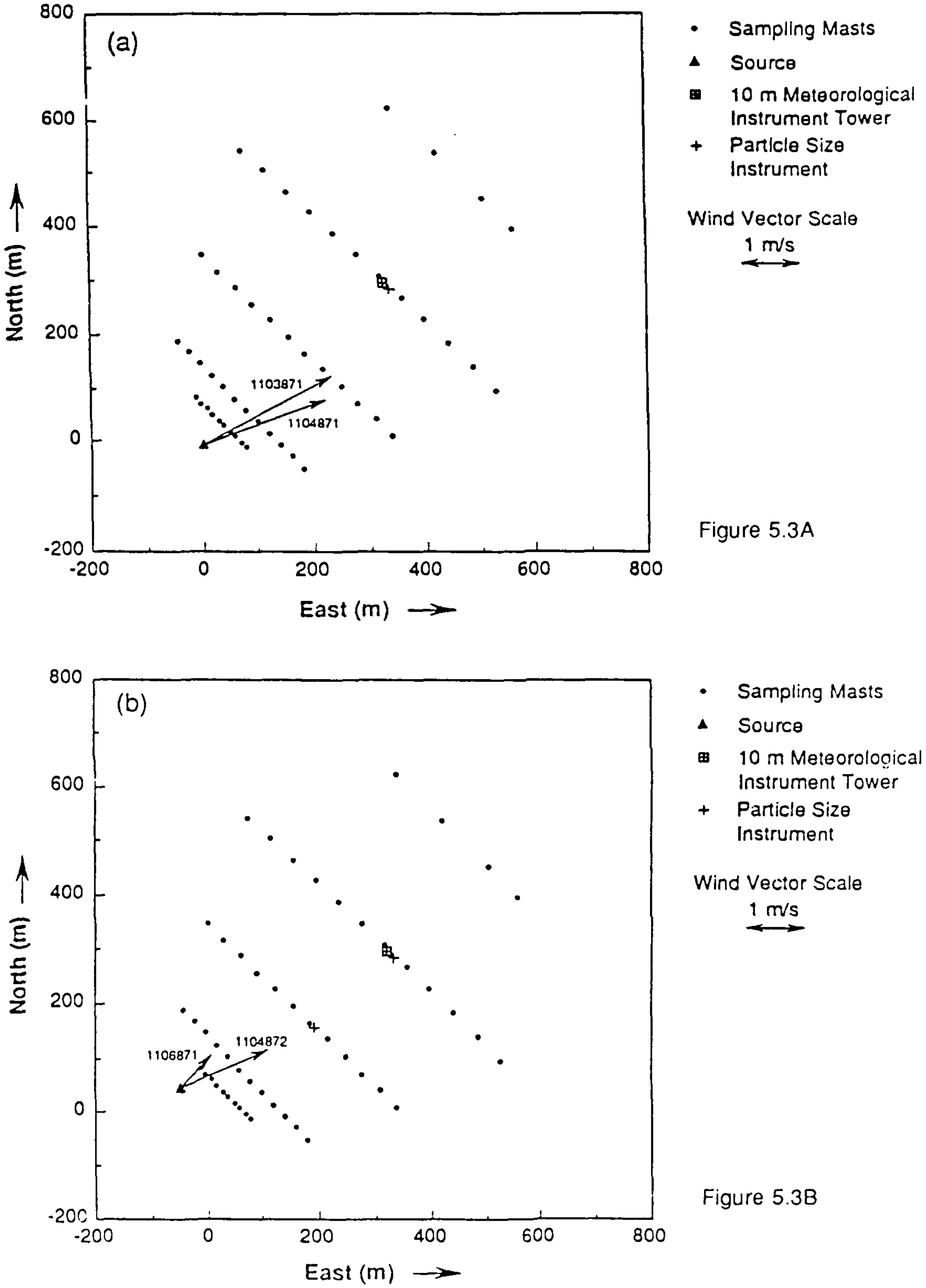
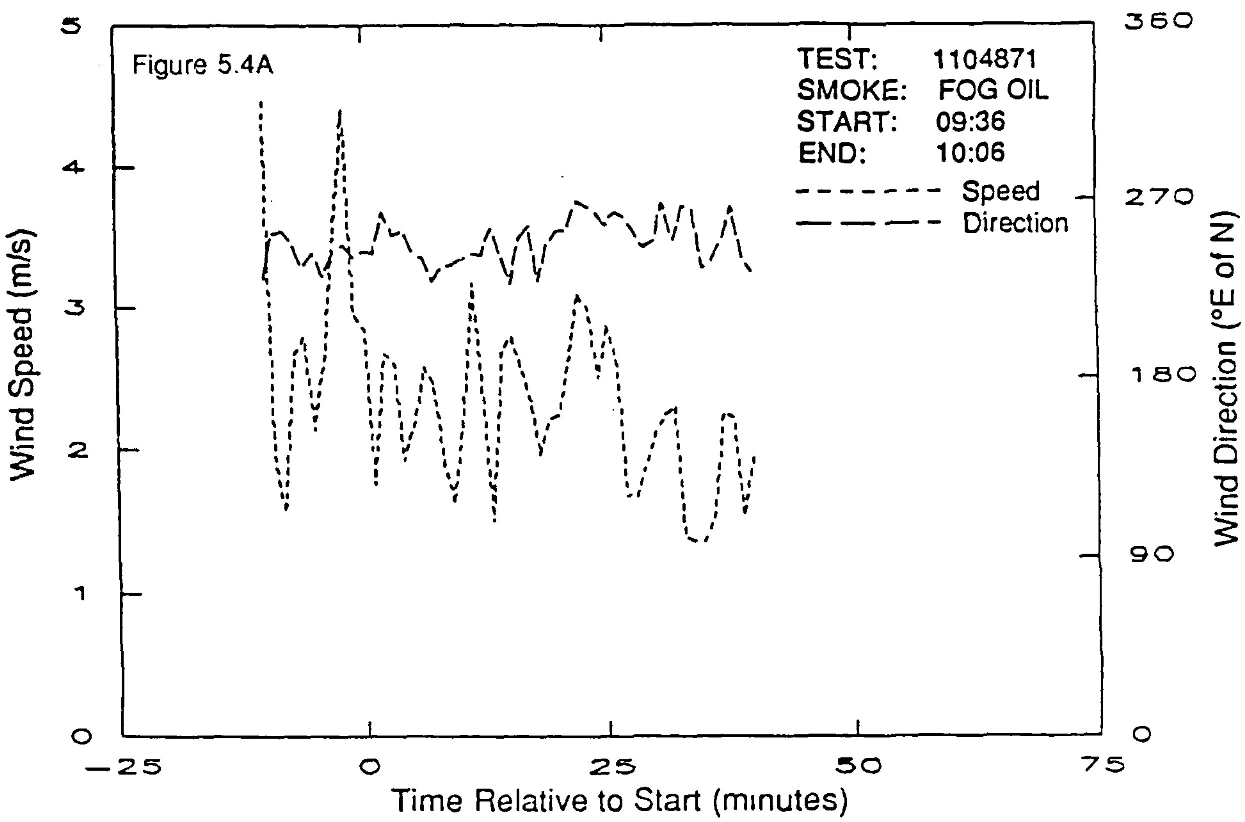


Figure 5.3 Enlargement of Fig. 5.1 showing equipment locations and average wind vector at source location for fog oil tests at Camp Atterbury; (a) 1103871 and 1104871, (b) 1104872 and 1106871. Grid zero is arbitrary.

Table 5.1 Summary of source data for fog oil tests conducted during Atterbury-87.

TEST:	1103871†	1104871	1104872	1106871
Source Location (m)	3.0, −4.7	3.0, −4.7	−47.7, 47.7	−47.7, 47.7
Mass Released (kg)	115.9	44.0	117.8	193.0
Release Duration (min)	55.9	27.5	48.2	76.2
Release Rate (g/s)	34.6	26.7	40.7	42.2
Exit Temperature (°C)	486	444	401	415
Wind Speed (m/s)	2.6	2.3	1.7	0.8
Wind Direction (°E of N)	241	249	247	224
σ_θ (°)	28.6	23.4	26.0	33.8
Temperature (°C)	23.4	20.0	25.3	8.0
Relative Humidity (%)	41	25	43	40

†Based on last five minutes of source data record due to equipment malfunction.



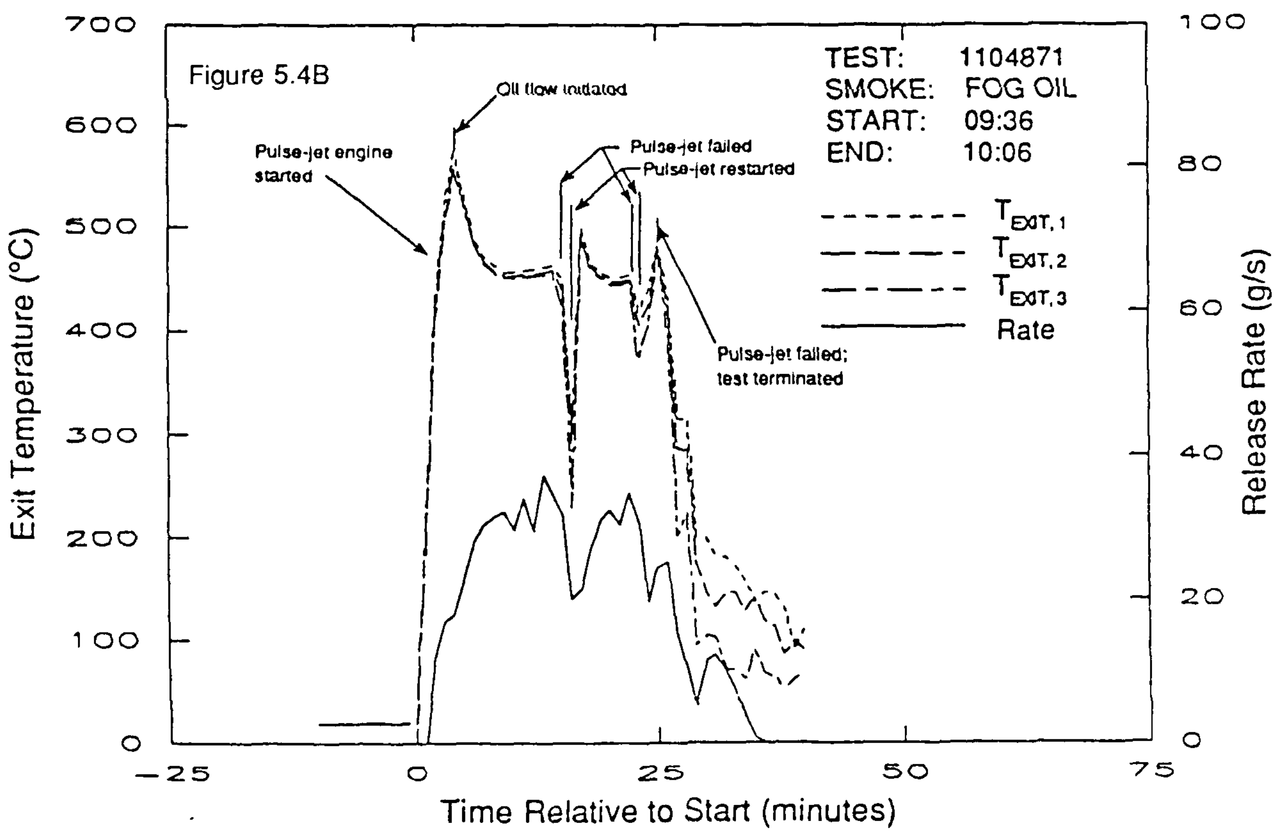
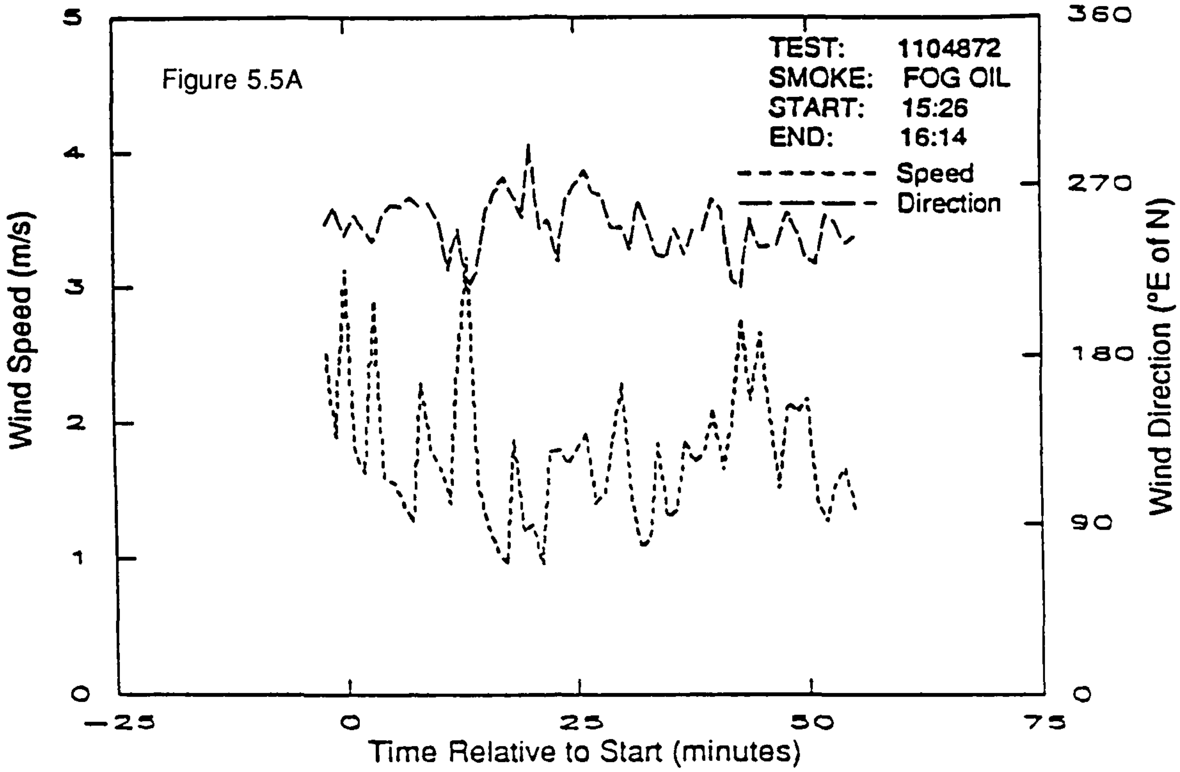


Figure 5.4 One-minute averaged source data for test 1104871 at Camp Atterbury. Top:wind speed and wind direction; bottom:exit port temperatures and release rate.



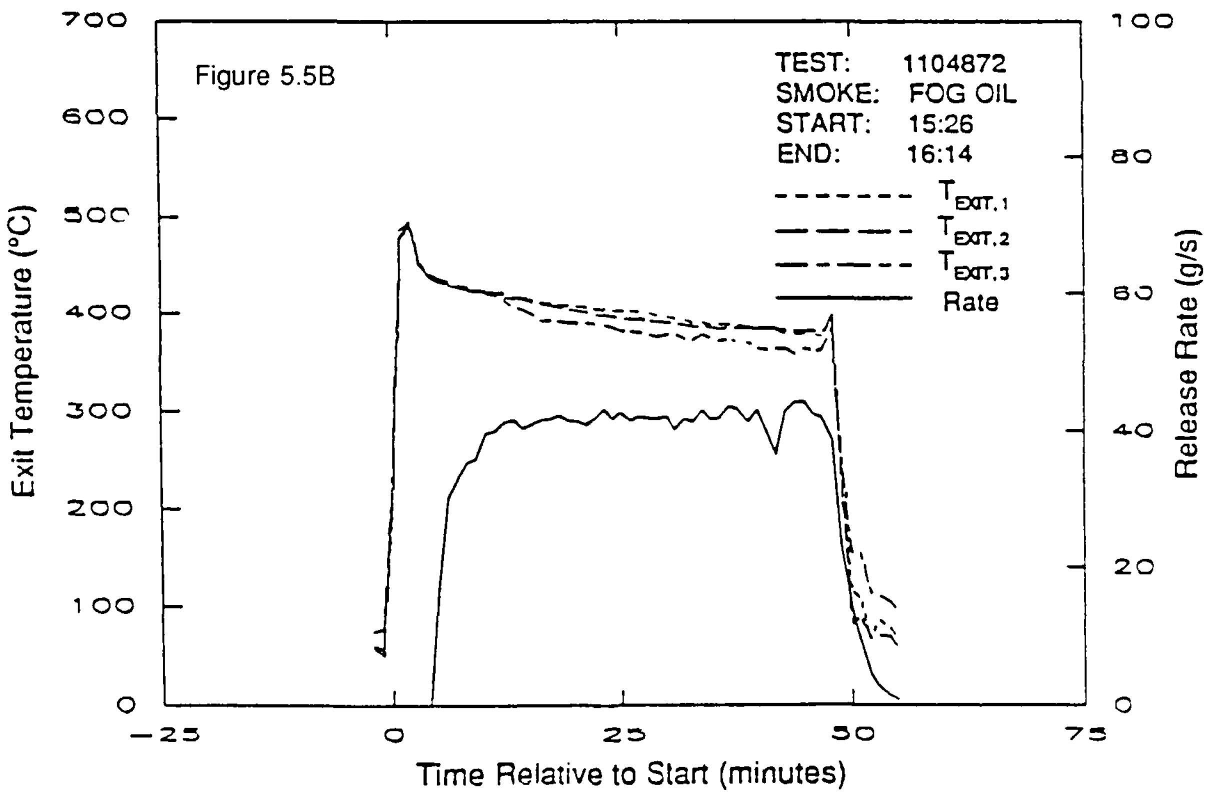


Figure 5.5 One-minute averaged source data for test 1104872 at Camp Atterbury. Top:wind speed and wind direction; bottom:exit port temperatures and release rate.

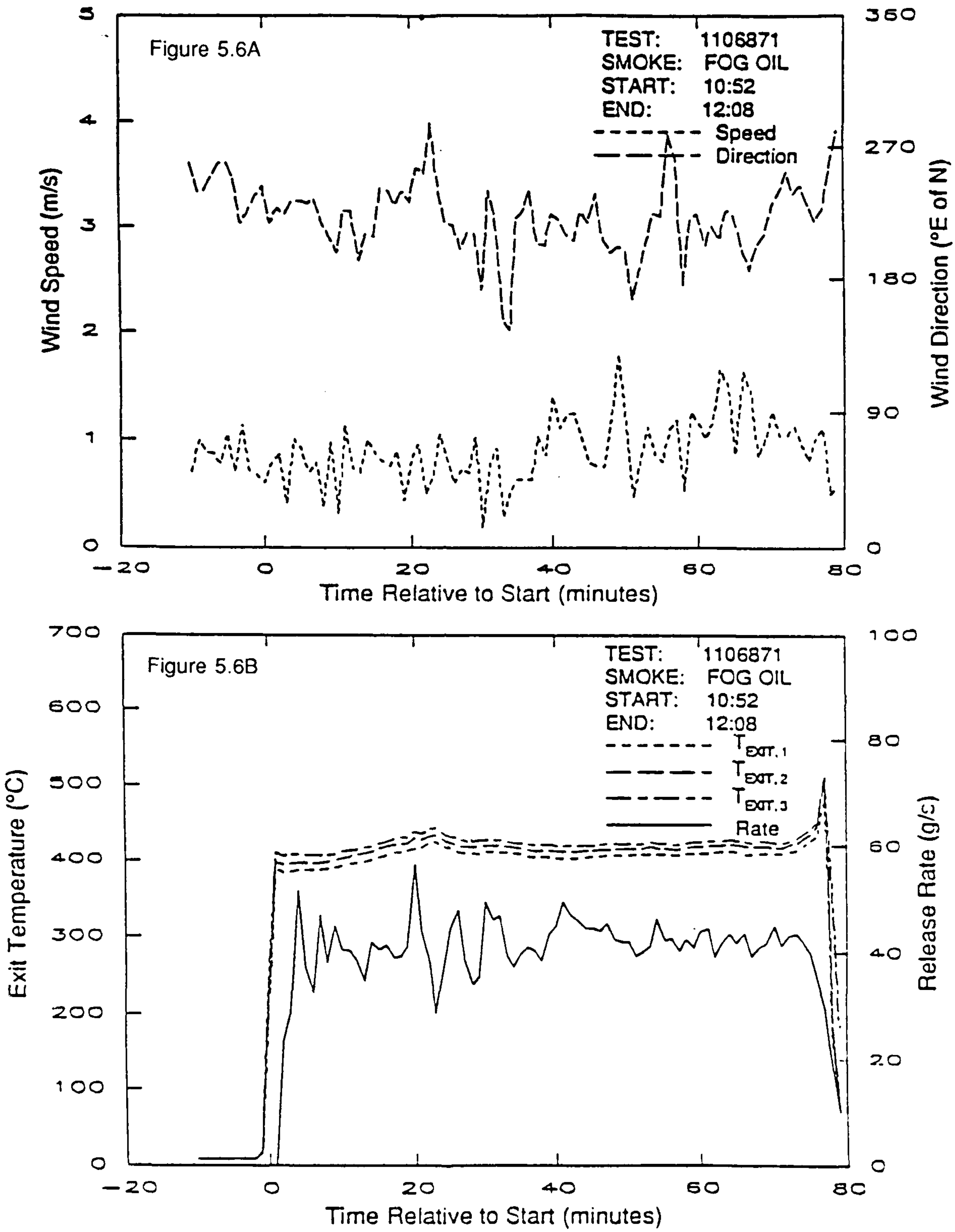


Figure 5.6 One-minute averaged source data for test 1106871at Camp Atterbury. Top:wind speed and wind direction; bottom:exit port temperatures and release rate.

record the digital output of the source data logger failed. As a result only that portion of the data record covering the last five minutes of the test could be recovered from the datalogger. Because the test was ultimately terminated by a failure of the M3A4 smoke generator unit, the average exit temperature during the last five minutes of the test may not be representative of the entire test.

Plots of the 1-minute averages of wind speed, wind direction, exit temperature and release rate are presented in Figs 5.4 to 5.6 for tests 1104871, 1104872 and 1106871 respectively. For test 1104871, Fig. 5.4a reveals that the wind speed was highly variable although the wind direction was fairly constant. As a result, the material plume tended to move downwind in pulses rather than as a uniform cloud. Fig. 5.4b confirms the previous statement that the M3A4 failed repeatedly during this test. Once the pulse-jet engine was started, the exit temperature climbed rapidly until the flow of fog oil was initiated. As the oil flow increased, the release rate increased as well and the exit temperature declined to a steady state value of approximately 450 deg C. About 18 minutes into the test, the pulse-jet engine failed for the first time, as indicated by the precipitous drop in exit temperature and release rate. The pulse-jet engine was restarted within one minute and the test continued. This pattern was repeated until after the third failure of the pulse-jet engine, whereupon the test was terminated.

As Fig. 5.5a and 5.5b indicates, test 1104872 was more successful. The wind speed and direction were very similar to the earlier test but the M3A4 performed much better. As before, the exit temperature shows an initial "spike" as the pulse-jet engine was started and allowed to warm up. Oil flow was initiated more slowly but increased gradually throughout the test, as indicated by the gradual decline in the exit temperatures. The variation in the measured exit temperatures among the three exhaust ports is due to small variations in the proximity of the thermocouples' measuring junction to the exit plane. The large dynamic pressure on the thermocouples due to the high exit velocity caused them to bend away from the exit plane. As the exhaust temperature declined rapidly with distance from the ports, small variations in the thermocouple positions produced significant variations in the measured temperatures.

The smoke generator performed flawlessly during test 1106871 (see Figures 5.6a and 5.6b). As Fig. 5.6b indicates, the wind speed was much lower than for the previous tests and the wind direction was highly variable and resulted in a much larger value for σ_θ in Table 5.1. Despite the variability of the wind direction, the smoke plume remained on the sampling network. Fig. 5.6b reveals that oil flow was initiated very soon after starting the pulse-jet engine and the exit temperature stabilized rapidly. The data also reveal that release rate was much more variable during the test. This is due to the lower ambient temperature (8 deg C vs. 25 deg. C) which correspondingly increased the viscosity of the fog oil. This in turn affected the ability of the fog oil pump to draw the oil from the supply drum and force it through a spray nozzle into the smoke generator. Interestingly, this does not seem to have had much effect on either the overall release rate or the overall exit temperature presented in Table 5.1.

Droplet-size data acquired during these fog oil tests show that the geometric mass mean diameter of the fog oil aerosol is about 1 micron. This implies that no deposition is expected (also verified in the Dugway and Camp Atterbury field tests); further, laboratory and field studies verify that no significant evaporation will occur over the distances that concentration data were obtained. Finally, the Dugway field tests and supporting laboratory studies done at the University of Illinois indicate that there is no significant vapor phase (less than 1% of mass emitted) to the fog oil emission. Consequently, the fog oil should act like a tracer with 99% contained in the aerosol phase.

6.0 COMPARISON OF MODELS WITH FIELD DATA TAKEN AT CAMP ATTERBURY

6.1 Preparation of Model Inputs

As in the Dugway field tests, the data from the source and meteorological towers were used to determine the required inputs to the four models. Table 6.1 presents a summary of the main source and meteorological variables for each of the four Camp Atterbury tests. As in the Dugway tests, all the models used 10 meter level wind speeds and directions, which were chosen based on discussions with the modelers. Pasquill stability classes are used in two models: BEAR and INPUFF-PG. Stability classes were all B except for case 1106871 which had stability class A. The RIMPUFF and INPUFF-Onsite models used

Test Designation	1103871	1104871	1104872	1106871
Smoke Type	Fog Oil	Fog Oil	Fog Oil	Fog Oil
Begin Test (CDT)	10:31:06	09:36:33	15:25:50	10:51:50
End Test (CDT)	11:27:00	10:06:00	16:14:00	12:08:00
Duration	00:55	00:29	00:48	01:16
Transects in Operation	1|2|3|4|5	1|2|3|4|5	1|2|3|4|5	1|2|3|4|5
Source				
Coordinates{x(m),y(m)}	3.0,-4.7	3.0,-4.7	-47.4,47.4	-47.4,47.4
Mass Released (kg)	115.9	44.0	117.8	193.0
Release Time (min)	55.9	27.5	48.2	76.2
Rate of Release (g/s)	34.6	26.7	40.7	42.2
2 m Wind Velocity (m/s)	2.6	2.3	1.7	0.8
2 m Wind Direction (°E of N)	241	249	247	224
2 m Sigma-theta (°)	28.6	23.4	26.0	33.8
2 m Ambient Temp (°C)	23.4	20.0	25.3	8.0
2 m Relative Humidity (%)	41	25	43	40
Particle Size				
Location[x(m),y(m)]	316.4,298.4	316.4,298.4	316.4,298.4	184.0,164.5
Mass Mean Dia. (μm)	0.96	-	0.67	1.01
Geometric Mean Dia. (μm)	0.86	-	0.56	0.90
Geometric Std. Deviation	1.55	-	1.71	1.53
Meteorology				
10 m Wind Velocity (m/s)	5.5	5.1	4.7	1.6
10 m Wind Direction (°E of N)	239	249	261	240
10 m Wind Inclination (°)	-10	-12	-11	-8
10 m Sigma-theta (°)	16.2	11.0	18.6	35.4
10 m Sigma-phi (°)	8.8	8.2	8.2	14.9
10 m Sigma-u (m/s)	1.52	1.17	1.26	0.70
10 m Sigma-v (m/s)	1.49	0.94	1.54	0.90
10 m Sigma-w (m/s)	0.94	0.82	0.78	0.49
10 m • 2 m ΔT (°C)	-0.41	-	1.89	-0.89
Wind Power Law Exponent	0.143	0.149	0.183	0.103
Est. Obukhov Lenght (m)	-5	-6	-3	-5
Est. Friction Velocity (m/s)	0.909	0.819	0.871	0.271
Est. Roughness Height (m)	0.20	0.20	0.20	0.20
Est. Inversion Height (m)	700	700	700	700
Est. Convection Velocity	2.53	2.25	2.07	1.29
zi/L = -k(w'/u')^3	-9.93	-8.53	-5.52	-44.00

Notes

1. All values are averaged over the period BEGIN-10 to END +10 minutes.
2. Only last 9 minutes of source data record is available for tests 1103871 & 1113871.
3. Only 20 minutes of met record is available for test 1104871.
4. No particle size measurements were obtained during test 1104871 due to insufficient smoke concentrations at the instrument location.
5. Convection velocity from Deardorff and Willis (1975) correlation
6. Negative mean wind inclinations reflect the mean subsidence flow observed under convective conditions (Liljegren 1989)

Table 6.1 Summary of data for four field tests at Camp Atterbury for fog-oil dispersion.

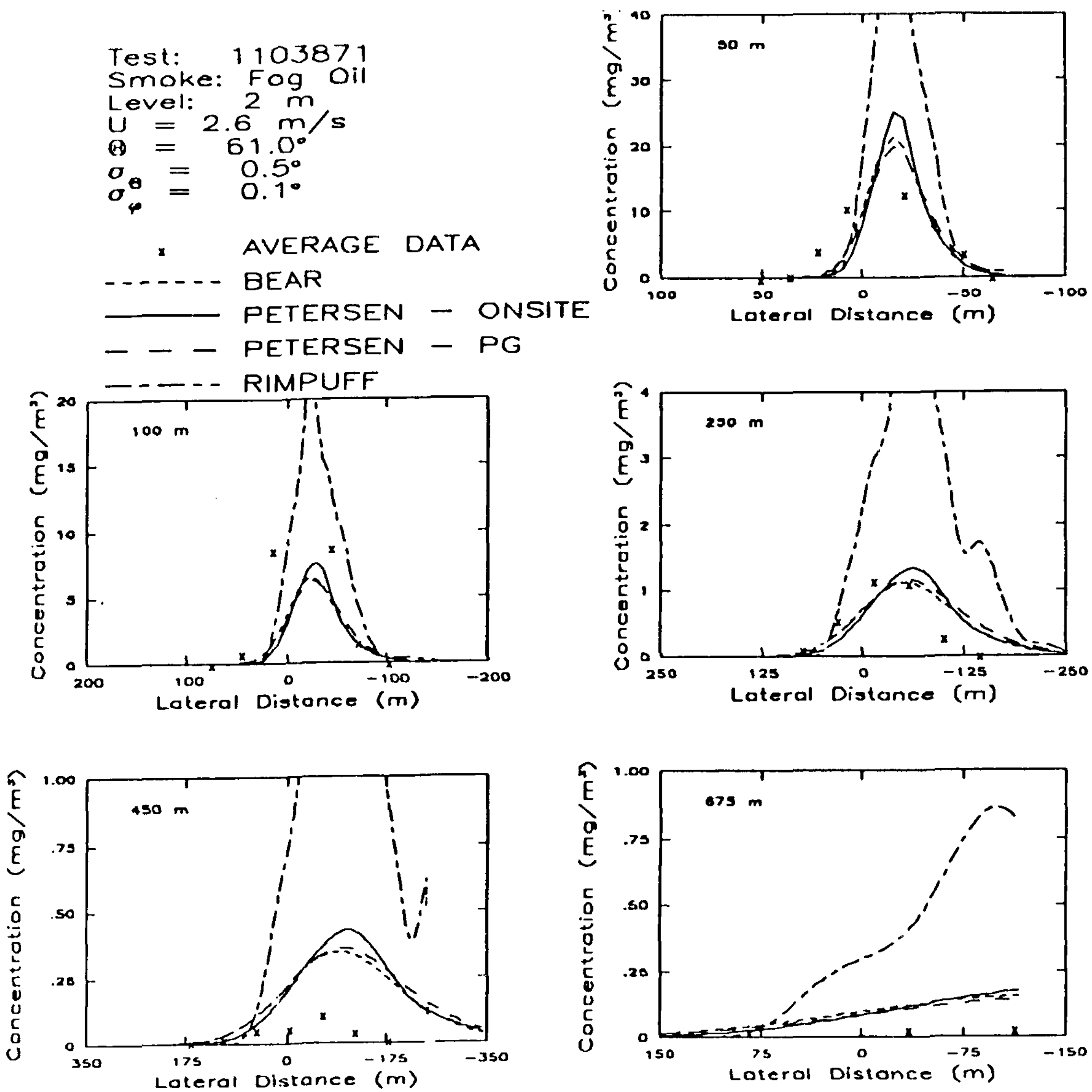


Figure 6.1. Comparison of RIMPUFF, BEAR, INPUFF-Onsite and INPUFF-PG mathematical models with average concentrations from test 1103871 at Camp Atterbury.

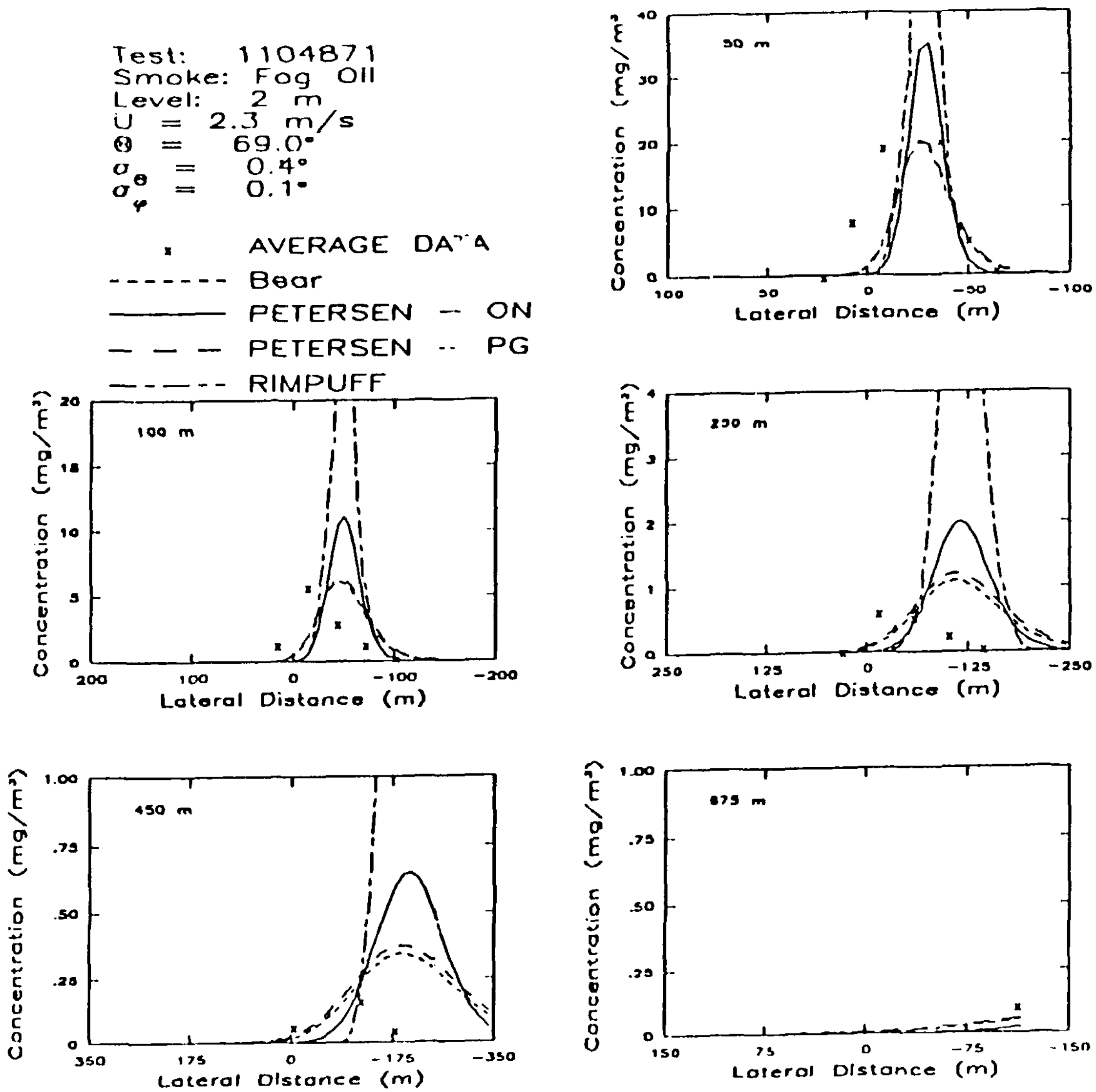


Figure 6.2. Comparison of RIMPUFF, BEAR, INPUFF-Onsite and INPUFF-PG mathematical models with average concentrations from test 1104871 at Camp Atterbury.

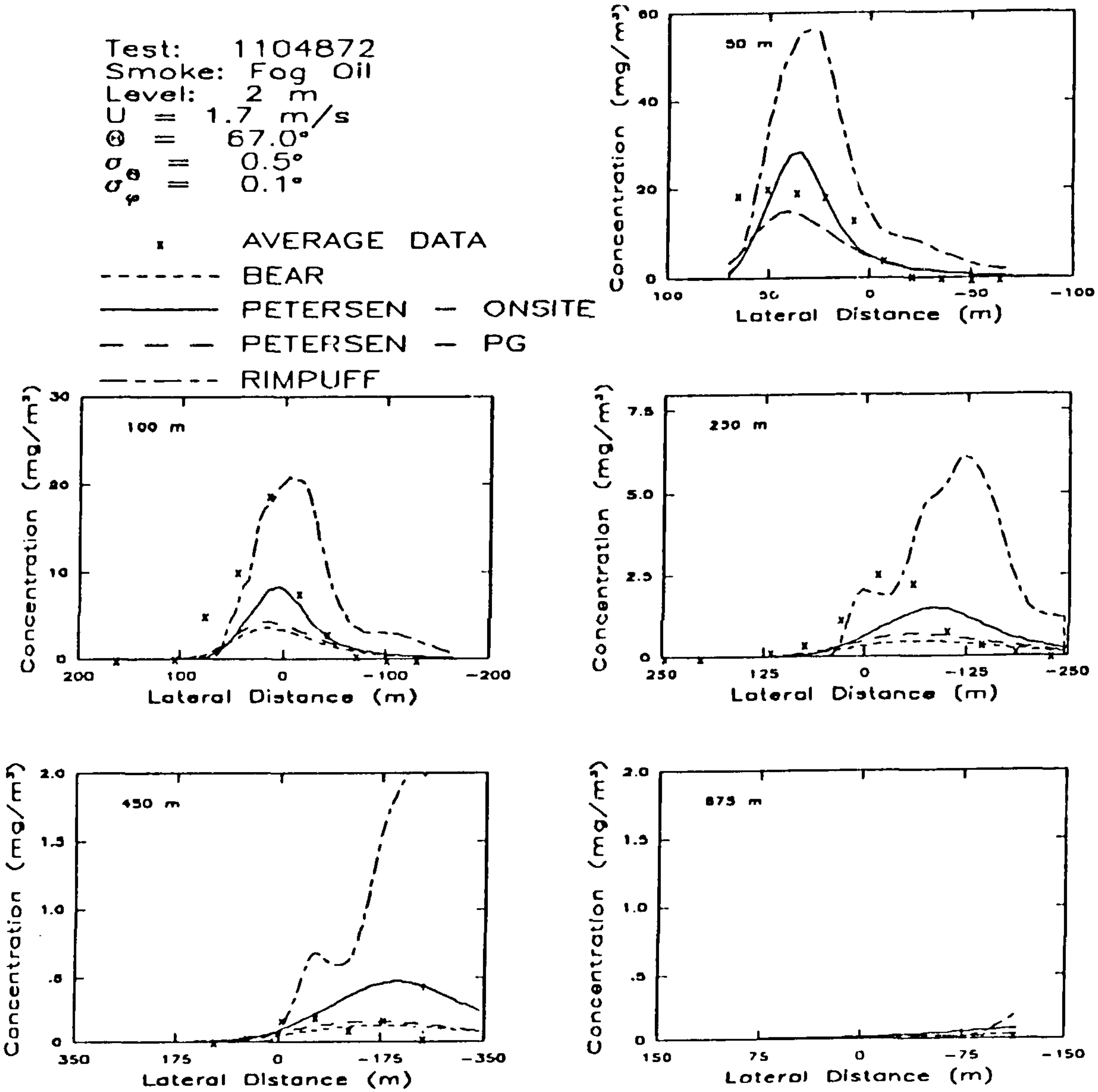


Figure 6.3. Comparison of RIMPUFF, BEAR, INPUFF-Onsite and INPUFF-PG mathematical models with average concentrations from test 1104872 at Camp Atterbury.

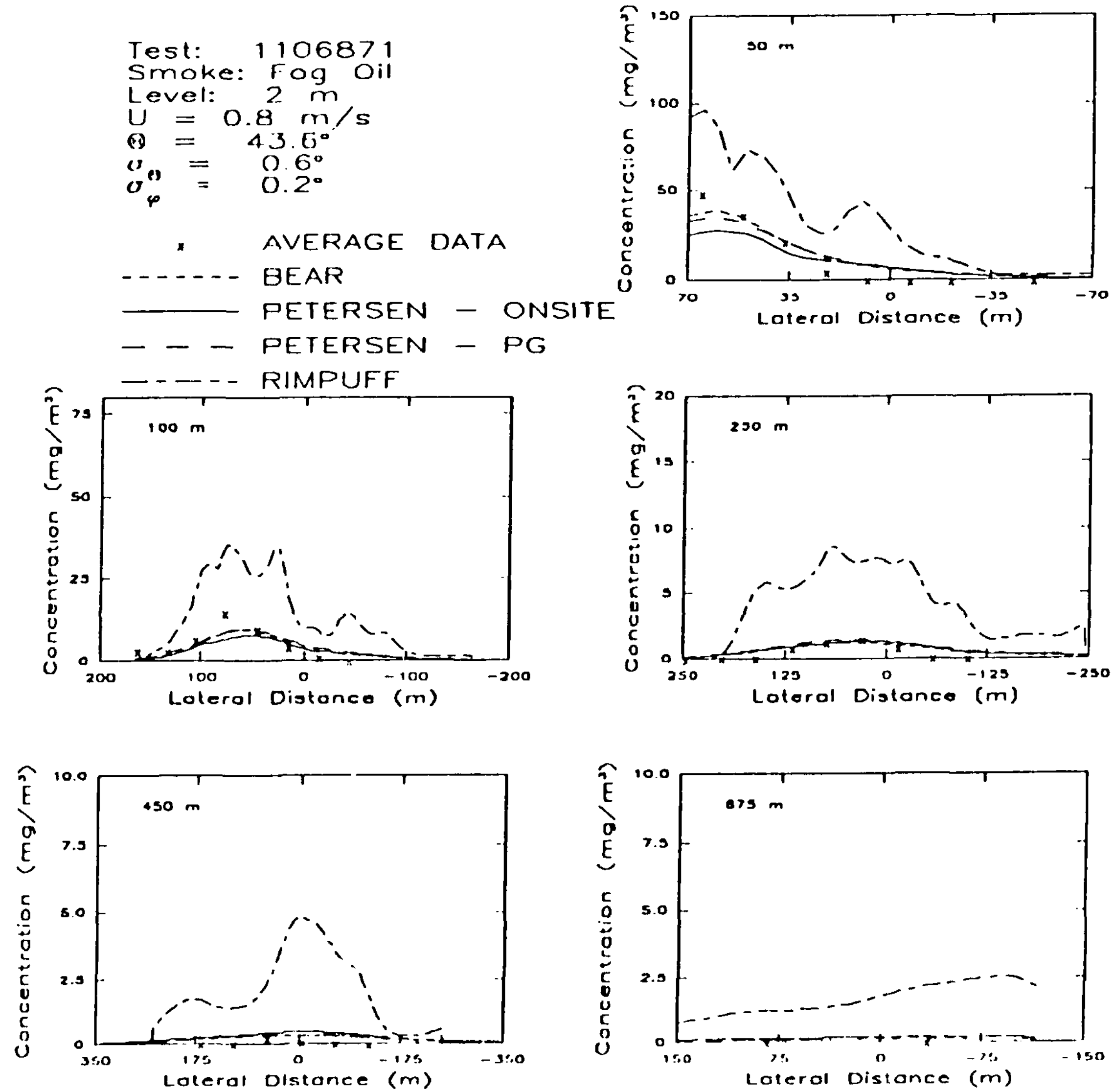


Figure 6.4. Comparison of RIMPUFF, BEAR, INPUFF-Onsite and INPUFF-PG mathematical models with average concentrations from test 1106871 at Camp Atterbury.

σ_θ and σ_ϕ values from the 10-m level as a function of time. As with the application of the models to the Dugway data, the RIMPUFF model used 15 second averaged meteorological data and the other three models used 3 minute averaged meteorological data. That data was available and provided to the model.

The release height was chosen to be 2 m above the ground for all models since it represented the observed height above ground of the center of the initial puff. The strong initial mixing that takes place and the slight buoyancy of the plume at exit leads to some uncertainty as to the effective height of release.

The release rate of fog oil as a function of time from the smoke generator was measured and was input to each of the four models. The exit temperature as a function of time was not used in the models since they could not use that information. The assumption of a nonbuoyant source, in the application of these models, precludes the use of those exit temperature data. In essence, the models are not complex enough in structure to require some of the measured data as input to the codes. More complex models may be tested in the future which would use all of the data measured. In any case, the data collected were necessary to develop a good understanding of the physics of the fog oil plume dispersion.

6.2 Results of the Model/Data Comparisons

Figures 6.1-6.4 present the comparisons of average concentrations with lateral distance for each of the four models at each of the five downwind transects. The following discussion can be made of those comparisons:

(a) Model agreement with the data is much better close to the source (at 250 m from the generator and closer) than further from the source (at the 450 and 675 m transects). The rise of the plume centerline noticed beyond about 250 m leads to much smaller concentrations measured than predicted. Model predictions assume that all puffs released will remain at the height of release at all distances downwind with no convective rise. The general overprediction of the models at the 450 m and 675 m transects is likely due to the lack of inclusion of convective rise of the puffs released from the generator,

(b) The BEAR and INPUFF-PG models are nearly identical in predictions for all cases. The theory of the models is very similar (both use the Pasquill-Gifford stability class method) and both use time-dependent winds at the 10-m level to transport those dispersing puffs,

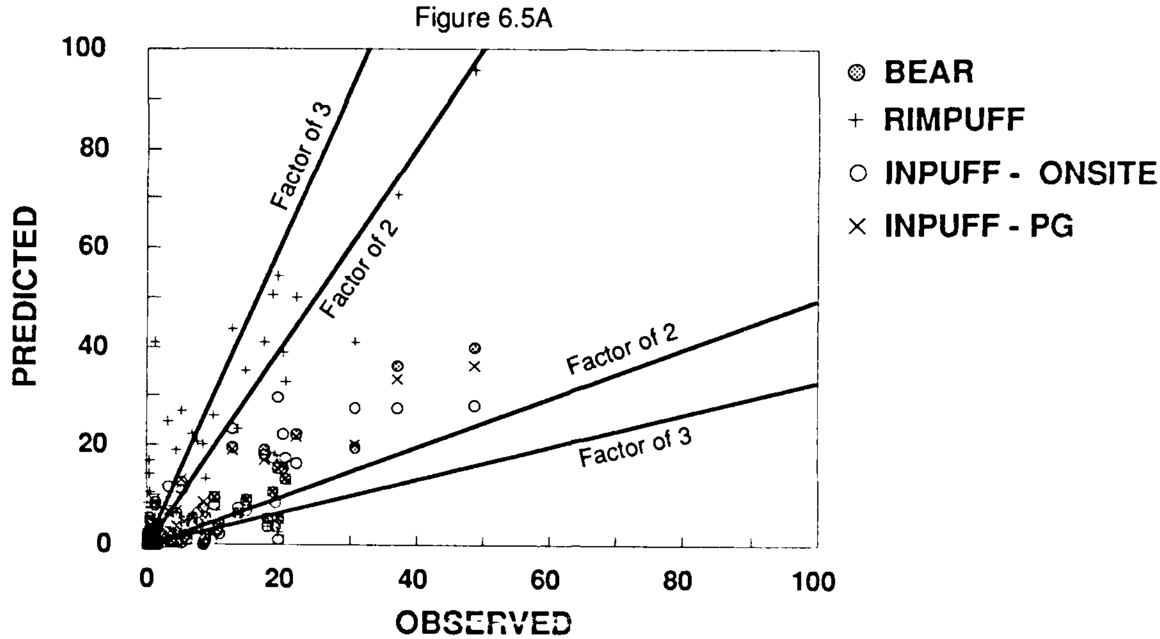
(c) The RIMPUFF model predicts higher average concentrations than the other models for most longitunal distances,

(d) The BEAR, INPUFF-Onsite, and INPUFF-PG models predict closer to each other than to the data. One may conclude from examination of the model/data comparisons that, for nonzero data values and all the models combined, the model predictions give 32% within a factor of two and 46% within a factor of three of the data .

One troubling aspect to the model/data comparisons is the generally poor agreement in the rate of concentration decay with distance between model predictions and data. At distances between about 50 and 250 m the model predictions are generally within a factor of two to three. However, for distances of 50 m or less, the models tend to significantly underpredict or, in some cases, overpredict the data. At distances beyond 250 m, the models tend to significantly overpredict the data and this disagreement is due, in part, to the rising centerline phenomenon.

The Gaussian puff models suffer from the assumption that the puff centerlines must always stay at the height of release and do not rise. There appears to be no judicious choice of the σ_z parameter of the Gaussian model to "correct" for the error of not allowing for a rising centerline. The data showed that the lateral distributions of concentration were approximately Gaussian in shape. The poor agreement between Gaussian models and the data for the rate of centerline concentration decay with distance underscores the fact that the vertical profile of concentration is not Gaussian in shape.

A final comparison of the Camp Atterbury average concentration data and the model predictions are given in Figure 6.5. This figure is actually a combined plot of results presented in Figures 6.1 to 6.4. The



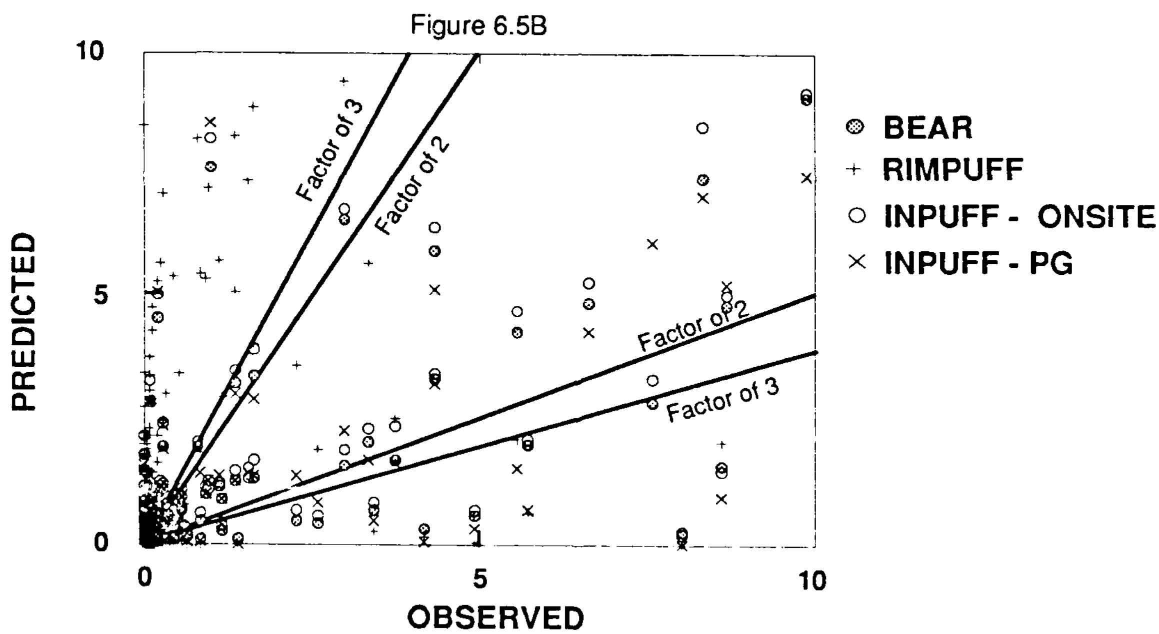


Figure 6.5 Scatterplot comparison of predicted and observed average concentrations for all four models to field data acquired for all four Camp Atterbury field tests.

45-degree line on the plot (not shown) represents perfect agreement between predictions and observations. The two factor-of-2 and the two factor-of-3 lines represent predictions that are a factor of two and factor of three greater or less than the observed values, respectively. Note, as in the Dugway tests, the large number of points within the factor-of-3 envelope. As in the Dugway comparison, many predicted/observed points are close to the origin. The typical range of precision believed representative of Gaussian model evaluations is a factor of two for 50% of the time. It can be said at this site, just like Dugway, that the particulate phase of the fog oil plume (for these short distances and stability classes B, C, and D) can be represented by the Gaussian dispersion model.

7.0 SUMMARY AND CONCLUSIONS

Seven data sets for fog-oil smoke dispersion in flat terrain have been used to test four Gaussian puff models. The models are simple in formulation and require time-dependent source and meteorological data for input. The models divide the release into a series of puffs which are dispersed and transported in the local wind direction. The puff centerlines remain at the height of release during their lifetimes but the puffs travel in directions that change with the wind direction data. The models differ in terms of their meteorological time-averaging period and their treatment of puff dispersion: use of Pasquill-Gifford stability classes, onsite turbulence data to provide direct estimates of dispersion coefficients (avoiding the P-G stability class scheme), or use of the Smith-Hay formulas for puff dispersion (also avoiding the P-G stability class scheme).

The data sets represent 3 data cases from the experiments at Dugway Proving Ground and 4 data cases from the Camp Atterbury experiments. Data were measured at several transects downwind in each experiment with the Dugway data obtained 25 m - 200 m downwind and the Camp Atterbury data obtained from 50 m - 675 m downwind. Smoke generator runs varied from 29-98 minutes. The concentration data represented average values over the period of the experiment. In the Camp Atterbury experiments, data were obtained at four levels from 1 m to 8 m . The Dugway concentration data were obtained at 2 m above the ground at all sampling stations.

The results show that the four Gaussian puff models tested can predict within a factor of three under the convective and neutral conditions tested to distances of about 250 m. Beyond that distance, the plume tends to rise leading the models to significantly overpredict average concentrations at ground level. No data were acquired at these two sites under stable conditions. (Fog-oil plumes under stable conditions were measured at the Meadowbrook site in Red Bluff, California but model testing with those data is not the subject of this report.)

The factor of two to three accuracy for this short-distance dispersion has been seen consistently for over the past twenty years with respect to point source tracer releases near the ground. The failure of the models to predict plume rise from the ground under convective conditions beyond about 250 m is a major flaw which needs to be emphasized. Given the accuracy of field data generally, the evaluation of the Gaussian models will yield similar results consistently, barring the possibility of poor source characterization. The present work adds to the state-of-the-art in that it is now shown that the particulate phase of a fog oil plume acts like a tracer in its dispersion in the atmosphere -- for the short distances and stability classes tested with the Dugway and Camp Atterbury data.

Although the Gaussian models tested with the fog-oil data indicated general agreement with the average concentration data within a factor of two or three for the average concentrations measured (for about 50% of data points), there were problems with the models (under these largely unstable atmospheric conditions) in that

(i) such agreement was only within the first 250 m from the smoke generator with more significant discrepancies at further distances,

(ii) there is a tendency to significantly overpredict or underpredict average concentrations at distances less than 100 m and to significantly overpredict at distances greater than about 250 m. The discrepancies found at longer distances (greater than about 250 m) is due to a rise in the plume centerline, and

(iii) the decay of concentration with distance as predicted by the models does not agree with the data and may be assumed to be, in part, the result of the rising centerline seen in the observed plume. The rising centerline phenomenon has been observed in other field and laboratory studies and cannot be represented by these Gaussian models. A new stochastic model tested with the data seems to replicate the systematic behavior in the data (including the rising centerline) quite well (Liljegren, 1989).

In a companion report by Liljegren (1989), a stochastic model is compared to the Camp Atterbury data and is shown to predict the rise of the plume under convective conditions quite well. The lack of treatment of convective turbulence in the Gaussian puff models is apparently the cause of the discrepancies between the model predictions and the data beyond about 250 m. Future work would involve the testing of complex terrain versions of all these models with both the stable and unstable plume dispersion data at the Meadowbrook site.

One difficulty with the application of the four Gaussian models to the seven data sets is the simple nature of the models tested. Indeed, simple models are needed for the practical and rather routine smoke plume modeling used by the U.S. Army. However, simple models are needed for some of the practical and rather routine smoke plume modeling applications used by The U.S. Army. Some of the questions that are raised in the application of these models to the Dugway and Camp Atterbury data sets are:

(a) Should the wind speed at the release height be used or is the 10-m value more representative? Or is an average over the height of the plume (at a given transect) more representative? An entire profile of such meteorological data is available from the experiments.

(b) What is the initial puff radius and height above the ground once the initial momentum of the plume exiting the three release ports is accounted for? What is the location of the passive diffusion source (perhaps located upwind of the smoke generator) that is "equivalent" to the source with initial momentum?

(c) What is the stability class for each experiment? The uncertainty in estimating the stability class is obviously present and the results are definitely dependent on the value chosen.

(d) How sensitive are the predictions to the kinds of uncertainties that have been identified in (a) and (c)?

There are no definitive answers to such questions (known at this time) and the models are clearly sensitive to the choices made. In any case, the most reasonable choice for each parameter was thought to have been made in applying the models to the data in this report. Furthermore, the agreement between the models and data remains reasonable for such flat terrain applications and short distances for which the models tested well (less than about 250 m). The accuracy of the Gaussian models is in doubt beyond that distance under unstable conditions. The problem in choosing the appropriate parameters for model input is inherent with those types of simple Gaussian puff models.

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APPENDIX A

"Comparison of Smoke Dispersion Model Predictions with Smoke Week Data"

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During these Smoke Weeks, one or two rows of aerosol photometer (AP)/chemical impinger (CI) pairs were placed downwind of the smoke generator. These rows were approximately normal to the plume centerline within about 100 m of the source. No data exist beyond this distance. Aerosol photometers measure concentration versus time through an optical scattering method. These instruments are fairly rapid in responding and, thus, are suitable for time-dependent concentration measurements, but their accuracy in terms of absolute concentration is poor. Thus, the AP readings were calibrated against measurements of dosage made simultaneously by the chemical impinger, i.e., the readings were scaled on a time-by-time basis such that concentration dosages are equal for each AP/CI pair. A brief description of the two Smoke Week sites and available data follow.

Smoke Week III was carried out at range C-52 at Eglin Air Force Base, Florida. Range C-52 has sandy soil, scattered pine trees and brush extended to an elevation of 16 m above ground level. Terrain in the vicinity of the 32-m meteorological tower was level and covered with grass, except for rutted roadways. Beyond the roadways there was a margin of grass with brush and small trees ranging from 0.5 to 3.0 m tall. At a distance of 300 m to the north, east, and south there was a thick pine forest 15-20 m tall on slightly rolling sand hills. The roughness length was estimated to be 50 cm for the lower levels of the 32-m meteorological tower and 30 cm for the upper levels. Roughness determination was complicated by wake effects of obstacles upwind.

Figures 2-4 present sketches of the layouts of the smoke generator, meteorological tower, and the aerosol photometer/chemical impinger system for the Smoke Week III and IV trials. The main sampling line (LOS 2) consisted of 101 chemical impingers (3 m apart) and 33 aerosol photometers (9 m apart). The auxiliary sampling line (LOS 3) consisted of 27 chemical impingers (6 m apart) and 9 aerosol photometers (18 m apart). Model/data comparisons are made here with the results of the chemical impingers. Future work will involve comparisons of models on a concentration versus time basis.

Not all the meteorological data measured for each trial could be used by the models. Available was a 32-m meteorological tower located at the center of the test grid which was equipped to measure

(a) horizontal and vertical wind directions at the 2, 4, 8, 16, and 32-m levels,

(b) horizontal wind speed at the 2, 4, 8, 16, and 32-m levels,

(c) temperature and dew point at the 2 and 32-m levels, and

(d) temperature difference between the 0.5 and 4-m levels.

COMPARISON OF SMOKE DISPERSION MODEL PREDICTIONS WITH SMOKE WEEK DATA

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ABSTRACT

Numerous mathematical models exist to predict the potential environmental impact resulting from the use of military smokes. Hazard prediction methods require the modeling of smoke dispersion at receptor locations typically 20 to 2000 m from the source. Accurate knowledge of smoke concentrations is also important for defining toxicological studies.

This paper provides a preliminary test of the performance of four mathematical models with dosage data from Smoke Week III Trials 4 and 19, and Smoke Week IV Trial 3. In these trials, fog oil was released from a M3A3 smoke generator. Although these data were not obtained for the explicit purpose of model evaluation, they represent the best data available at the present time for this purpose. More extensive data are being obtained as part of the present project.

The Smoke Week data used for model testing represent fog-oil trials. In a typical trial, 10 to 100 dosage samplers are set out along one or two transects approximately normal to the plume centerline at distances of about 50-80 m downwind. Meteorological data from a 32-m (45-m in Smoke Week IV) instrument tower were also available.

The models tested are COMBIC, ACT II, MAD Puff, and the Ludwig (1977) model. All models are of Gaussian type. COMBIC, ACT II, and MAD Puff are applied to meteorological data that have been time-averaged over the period of smoke release. The Ludwig Model, on the other hand, is applied to time-varying meteorological data over the trial period. COMBIC and ACT II model predictions have straight line trajectories. However, the MAD Puff and Ludwig Models have variable trajectories due to the modeling of turbulence along the trajectory (for MAD Puff) and the treatment of time-varying wind direction for the Ludwig Model.

Model/data comparisons reveal that all four models are within factors of 2-3 in predicting dosages at each of the rows of samplers. In general, the models tend to underestimate lateral spreading and have their predicted peak values offset from the data. It was found that for such short release times and for the prediction of dosages, the lateral movement of puff centers due to turbulence (in MAD Puff) or by time-dependent wind direction variations (in Ludwig) do not appear to improve model performance. Unfortunately, the rows of samplers were all very close to the generator; no data exist beyond about 150 m from the source. Future measurements should include the fog-oil release rate from the generator. For Smoke Week III, Trials 4 and 19, the nominal 40 gal/hr rate of release had to be assumed since no measurements of release rate or total fog oil consumed were made for those trials.

1. INTRODUCTION

The current research project addresses the need of the US Army Medical Research and Development Command to predict dosages and deposition rates to civilians and indigenous plants and wildlife resulting from the use of military smokes in field training exercises. To meet this need, two project objectives are set forth: (1) carry out a comprehensive field measurement program to obtain high quality data on the dosages and deposition rates resulting from smoke emitted by specific military smoke generating devices, and (2) use these field data, combined with results which can be synthesized from other studies of smokes, to evaluate the performance of predictive models. Results to date of the field effort described in (1) are given in Dunn et al. (1985).

The initial effort of the model evaluation program has focused on testing model predictions with data from Smoke Weeks III and IV. This effort not only provides experience with the use of the models but more importantly highlights critical modeling and data issues. The range of variability among the predictions of alternative modeling approaches is also being documented. Further, sensitivity tests will indicate which parameters need to be most accurately measured in our field studies. The effort will establish a framework for the evaluation process itself including the use of graphical and statistical presentations of model/data comparisons.

This paper summarizes the early efforts under this model evaluation plan. Consistent with overall project objectives, the focus has been on the evaluation of models for fog-oil plume dispersion in flat terrain. The specific data sets used in model testing are Smoke Week III, Trials 4 and 19 along with Smoke Week IV, Trial 3. Model/data comparisons were made for concentration dosages along one (Smoke Week IV) or two (Smoke Week III) horizontal lines of sight (LOS). The models tested were COMBIC (Hoock et al., 1982), ACT II (Sutherland and Hoock, 1982), MAD Puff (Matise et al., 1982), and the Ludwig Model (Ludwig, 1977).

Future work will involve the testing of other U.S. Army models including HECSMOKE-I (Cheney and Dumbauld, 1979), HAZRD-2 (personal communication, July 1984, Mr. Ronald Pennsyle, Chemical Research and Development Center, Aberdeen Proving Ground, Maryland), SEMM (Marchetti, 1979, 1980, 1981), MoCaPD (Huang and Frost, 1982), the Ohmstede-Stenmark (1981) Model, the Ludwig (1983) Model, and MSMOKE (Hansen, 1984). Models developed outside the U.S. Army community which show special promise for fog-oil dispersion calculations will be evaluated as well. Models with such unique theoretical features are the Dunn-Boughton Model (1984), the Riso Puff Model (Mikkelsen and Larsen, 1984), and the Petersen (1984) Model. All models will be tested with the above Smoke Week data along with new data obtained as part of the ongoing field work.

2. MODEL FORMULATIONS

In this paper, four models are tested with field data on measured concentration dosages: COMBIC, ACT II, MAD Puff, and Ludwig (1977). ACT II and MAD Puff were provided to us by Optimetrics Inc. as part of the ACTMAD computer model. If run in its ACT II mode, it is identical to the standard ACT II model (Sutherland and Hoock, 1982) with only a few minor alterations. If run in its MAD Puff mode, it uses the MAD Puff turbulent transport methodology to be discussed below. The COMBIC Model was obtained from the Atmospheric Sciences laboratory and the Ludwig Model was obtained from Dr. Ludwig at the

Stanford Research Institute. The Ludwig (1977) Model is also referred to as the Behavior of Environmental Aerosol Releases (BEAR) Model and is the most appropriate of the Ludwig models to be tested with the Smoke Week data.

The key features of each of the four models are compared in Table 1. As may be seen, the COMBIC, ACT II, MAD Puff, and Ludwig Models are all of Gaussian type. In COMBIC, the continuous plume (rather than the puff formulation) is applied to fog oil released from smoke generators. The model developers believe that releases of 10 seconds or greater are best simulated with a continuous plume formulation. They cite the fact that observed fog-oil plumes do not have a leading edge or trailing portion outside of the main body of the plume. Except for the lowest wind speeds, longitudinal advection dominates longitudinal diffusion. As a result, diffusion in the longitudinal direction need not be modeled. The ACT II, MAD Puff and Ludwig Models simulate the generator effluent as a series of discrete puffs during the time of generator operation. The advantage to a puff release simulation is that a time varying release can be more accurately treated.

TABLE 1. COMPARISON OF THEORETICAL FEATURES OF COMBIC, ACT II, MAD PUFF, AND LUDWIG (1977) MODELS FOR FOG-OIL APPLICATIONS

Model	Approach	Formulas for σ_x, σ_y, and σ_z	Meteorological Data Input	Plume Rise	Deposition	Uses Measured Turbulence Quantities, σ_θ and σ_ϕ
COMBIC	Gaussian Plume	Continuous plume	Steady state	No	No	No
ACT II	Gaussian Puff	Continuous plume	Steady state	No	No	No
MAD Puff	Gaussian Puff with Random Trajectory Methodology	Instantaneous puff	Steady state	No	No	Yes
Ludwig (1977)	Gaussian Puff	Continuous plume	Time dependent	Yes	No	No

Both ACT II, COMBIC, and MAD Puff Models require the use of time-averaged meteorological data; as a result, the models are applied to a pseudo steady-state meteorological system. For all three models, the time-averaging is done over the period of operation of the smoke generator. The Ludwig Model permits as input time-dependent meteorological data in its puff formulation. Each time that new meteorological inputs are read, a new time step for the release of puffs is determined. The Ludwig treatment permits the simulation of changing wind speeds and directions during the period of smoke generation. As a result, plume meander is treated by means of this time-dependent formulation.

In spite of the fact that time-averaged meteorological data are used in MAD Puff, the model uses measured turbulence quantities (σ_θ and σ_ϕ) to add random transport components to the trajectory of each puff. In the MAD Puff mode, the puffs are moved in a semi-random fashion based upon a turbulent fluid parcel transport theory developed by S.R. Hanna (1979). As a result, each puff has a variable trajectory based on the simulation of atmospheric turbulence. The growth of the puffs with downwind distance is, however, based on the plume dispersion parameters, σ_x, σ_y, and σ_z.

COMBIC and ACT II provide smooth Gaussian plumes with a straight-line trajectory for the continuous plume (COMBIC) and puffs (ACT II). MAD Puff and Ludwig create inhomogeneous plumes by means of their variable puff trajectory formulations. MAD Puff uses a simulation of atmospheric turbulence to provide the randomness whereas the Ludwig Model employs time dependent wind speeds and directions. Figure 1 provides a characterization of the smoke plumes predicted by each model as compared to a "real" smoke plume.

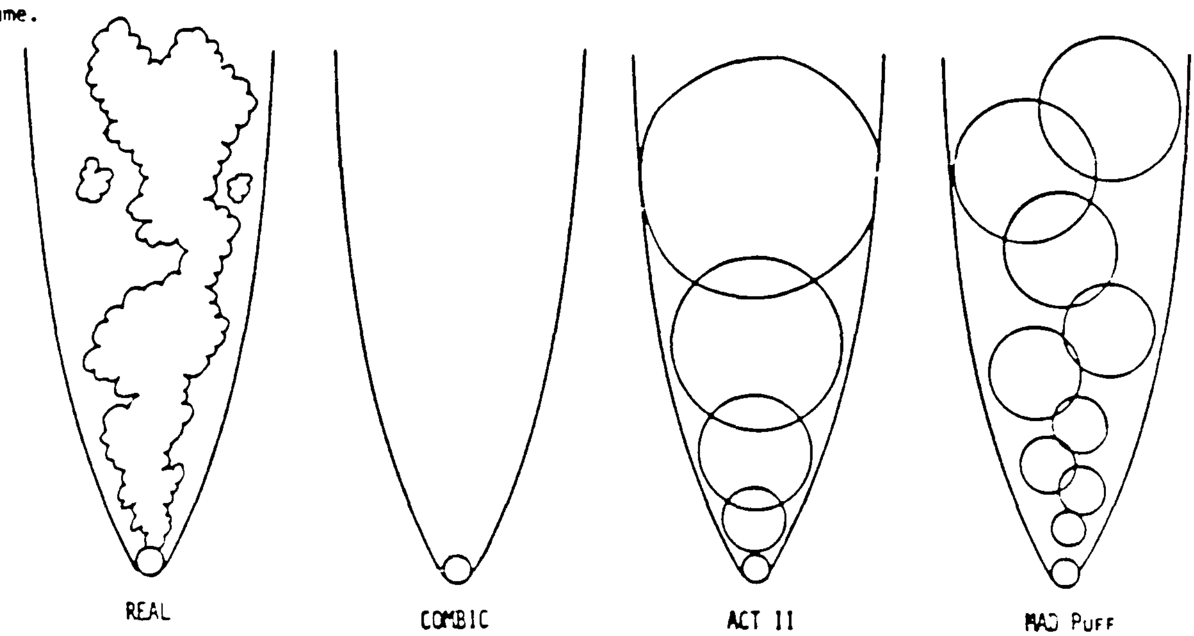

FIGURE 1. SMOKE PLUME CHARACTERIZATION OF COMBIC, ACT II, MAD PUFF, AND LUDWIG (1977) AS COMPARED TO A TYPICAL "REAL" PLUME

Each of the above four Gaussian Models uses different power-law formulations for the horizontal and vertical dispersion coefficients. The COMBIC Model uses the σ_y and σ_z coefficients recommended by

Hansen (1979) for continuous plumes. In this notation, x is downwind, y is crosswind, and z is vertical. Due to the continuous Gaussian plume assumption for fog-oil plumes, COMBIC assumes $\sigma_x=0$. For the ACT II puff release., the continuous plume sigmas from the Hansen (1979) reference are used but with $\sigma_x=\sigma_y$. Ludwig uses continuous plume sigmas for his puffs; $\sigma_x=\sigma_y$ is assumed with variations with downwind distance obtained from Turner's workbook (1969). The σ_z values used by Ludwig are a modification of Turner's values for each stability class. In the COMBIC and ACT II Models, σ_z is a function of roughness length in addition to stability class.

The plume sigmas used by the COMBIC, ACT II, and Ludwig Models were obtained from data on long-term time averages of steady-state plumes; these sigmas include the effects of the low frequency wandering of the plume as well as small-scale diffusion. The MAD Puff Model attempts to simulate the meandering of the plume separately from small-scale diffusion processes. As a result, the sigmas used by MAD Puff represent those of instantaneous puffs where essentially the effects of the low frequency meandering have been removed from the sigmas obtained from long-term averaging. The formulas for the instantaneous puff sigmas are also obtained from Hansen (1979). From Hansen, the growth rate of the instantaneous puff sigmas is simply 2/3 the growth rate of the long-term sigmas for the y and z directions with a factor of 0.74 used for the σ_x growth formula. As a result, σ_x is greater than σ_y in the MAD Puff formulation. Clearly, the different simulations of dispersion among the models will lead to differences in model predictions.

The COMBIC, ACT II and Ludwig models assume complete reflection of the plume at the ground surface. The option for complete reflection was chosen in the fog-oil runs for MAD Puff. No deposition of fog oil is also assumed. The Ludwig Model has a built-in treatment for plume rise whereas the user in COMBIC, ACT II, and MAD Puff suppresses the treatment of plume rise for fog-oil applications with his choice of input parameters.

3. SMOKE WEEK III AND IV DATA

Three trials were chosen for the purpose of comparing model predictions with data. These are Smoke Week III, Trials 4 and 19, and Smoke Week IV, Trial 3. These trials employed the M3A3 smoke generator. Data from these trials were obtained largely from the Atmospheric Aerosol and Optics Data Library (AAODL) of Science and Technology Corporation with supporting information from OPM Smk/Obs (personal communication, August 1984, Mr. Howard Smalley, Aberdeen Proving Ground, Maryland), Burgess and Nielsen (1[illegible]), and Nelson et al. (1982).

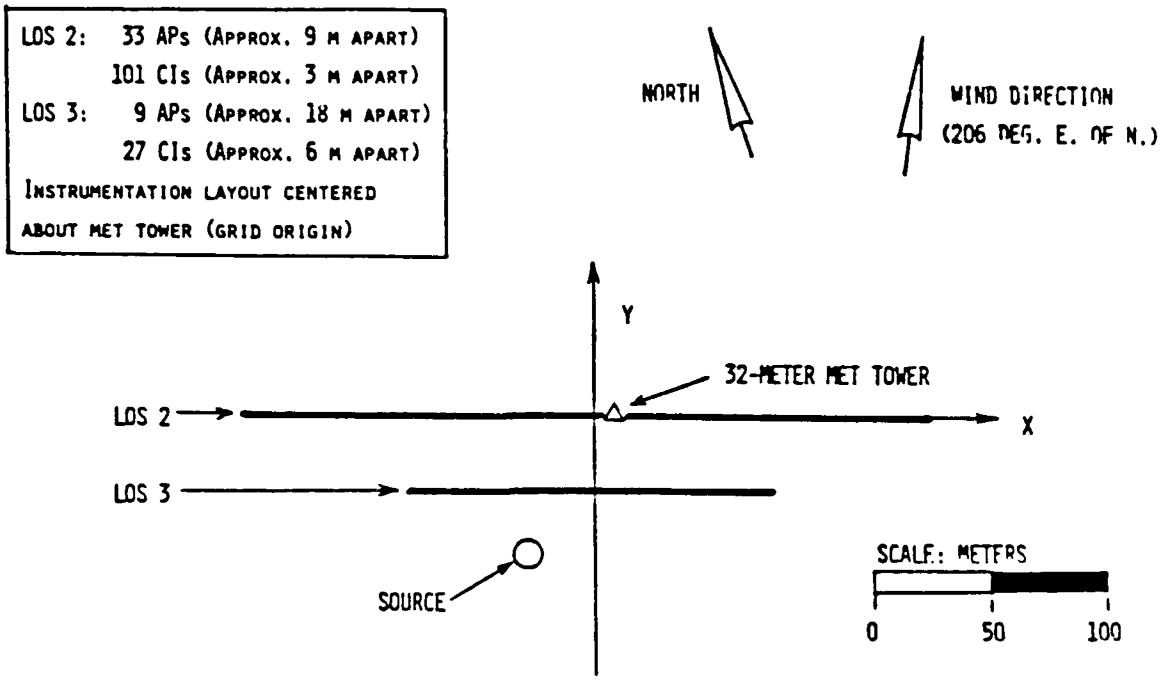

FIGURE 2. CONFIGURATION OF SOURCE, RECEPTORS, AND METEOROLOGICAL TOWER FOR SMOKE WEEK III, TRIAL 4

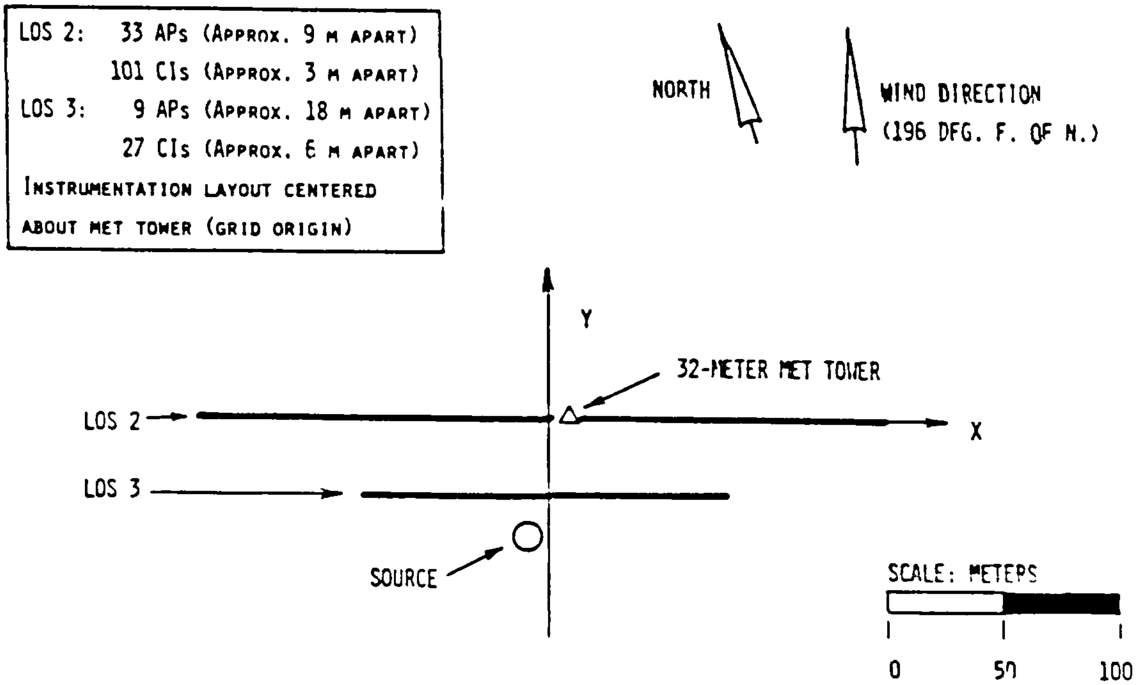

FIGURE 3. CONFIGURATION OF SOURCE, RECEPTORS, AND METEOROLOGICAL TOWER FOR SMOKE WEEK III, TRIAL 19

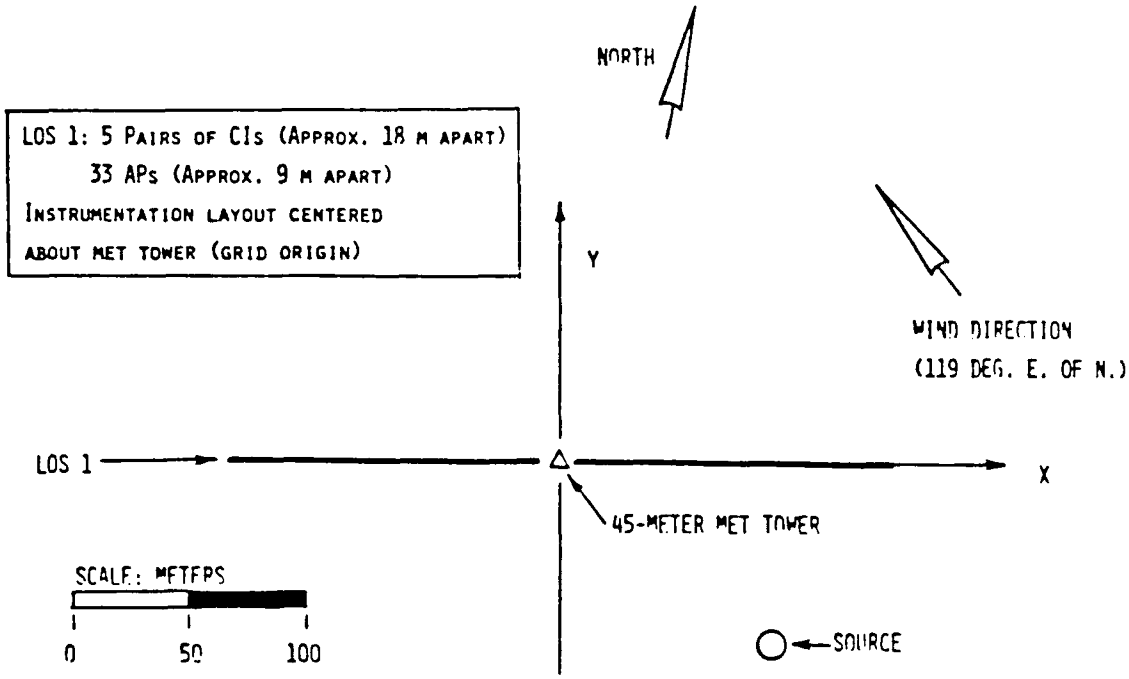

FIGURE 4. CONFIGURATION OF SOURCE, RECEPTORS, AND METEOROLOGICAL TOWER FOR SMOKE WEEK IV, TRIAL 3

In addition, four 2-m meteorological masts located along the main sampling line were equipped to measure horizontal wind direction and wind speed. Each of the models used only wind speed and direction at a 10-m elevation obtained by interpolating the 8 and 16-m wind data on the meteorological tower. The wind profile exponent computed from the measured wind profile was used as an input parameter by the ACTMAD Model. Pasquill stability categories were determined using the Turner method based on wind speed and solar radiation index, modified by cloud cover and cloud height. None of the mast data or individual wind measurements at different tower levels could be input to the models.

The Smoke Week IV tests were conducted at Test Area 1 (TA-1) at Redstone Arsenal, Huntsville, Alabama. TA-1 is a relatively flat, open field approximately 6 km long and 1-2 km wide. Part of the test area was damp, and the lowest areas contained pools of water. TA-1 is surrounded by dense hardwood forest. Tree heights are typically 10 m. In the Smoke Week IV tests, only one line of samplers was used associated with LOS 1 of the total of four optical lines of sight. Figure 4 provides a sketch of this sampling line, the 45-m meteorological tower, and the generator location. On the sampling line were 33 aerosol photometers and 12 aerosol samplers (chemical impingers and/or filter samplers).

Samplers were positioned in pairs at five points along LOS 1 with two on a mobile measurement unit, 1.5 m above ground. The sampling line also had 33 aerosol photometers at 9-m intervals.

A 45-m meteorological tower was located at the center of the sampling line and was equipped to measure the following:

(a) temperature and dew point at the 2 and 32-m levels,

(b) temperature at the 0.5, 2, 4, 10, 16, 32, and 45-m levels,

(c) horizontal components of the wind direction and speed at the 2, 4, 10, 16, 32, and 45-m levels, and

(d) vertical component of wind direction at the 10 and 32-m levels.

σ_θ was available at the 2, 4, 10, 16, 32, and 45-m levels while σ_ϕ was available only at the 10 and 32-m levels. A wind profile exponent required by ACTMAD was available from the wind data. Atmospheric stability was provided in terms of Pasquill categories determined as before from sky conditions and the 10-m wind speed.

4. PREPARATION OF MODEL INPUTS

As noted above, each model has special input requirements which utilize a subset of the available data. Considering that COMBIC, ACT II, and MAD Puff require meteorological data that are averaged over the generator run time, their input data are quite similar. Table 2 lists the key input to those models. All models including that of Ludwig require wind speed and direction at the 10-m level. The Ludwig Model is different in that it requires a time-dependent input. Meteorological data were input to that model in five second intervals. To be noted from Table 2 is that all three cases happen to represent stability class C. Also, an assumption of 40 gal/hr of fog oil release from the generator had to be assumed for Smoke Week III, Trials 4 and 19. No data on fog oil use were measured in those experiments. The data from Smoke Week IV, Trial 3 reveal only a 24 gal/hr release rate. Generator operation times were short varying from only 5 to 11 minutes. Longer periods of release are of interest for health effects research; such longer periods would likely have the wind vary in direction much more and lead to a greater challenge for the models.

TABLE 2. SUMMARY OF KEY MODEL INPUTS FOR COMBIC, ACT II, MAD PUFF AND LUDWIG (1977) MODELS AS APPLIED TO THE SMOKE WEEK III AND IV DATA SETS

Input Parameter	Smoke Week III Trial 4	Smoke Week III Trial 19	Smoke Week IV Trial 3
Wind speed (10 m), m/s	5.0	3.7	4.0
Wind direction (10 m), deg	206	196	119
Wind speed power law exponent	0.11	0.14	0.116
Stability class	C	C	C
Roughness height, cm	50	50	10
Generator release rate, gal/hr	Not measured*	Not measured*	23.8
Generator run time, min	7	11	5
Location of X axis (line of samplers), deg east of north	108	108	74
Grid origin (0,0)	32-m met tower	32-m met tower	45-m met towe
Generator coordinates, m	(-30, -60)	(-15, -50)	(90, -80)

*It was assumed that the nominal value of 40 gal/hr was the release rate of fog oil.

Special Parameters (for MAD Puff) only:

Friction velocity, m/s	0.7	0.7	0.5
σ_θ, deg (at 4-m level)	12.6	13.6	8.0
σ_ϕ, deg (at 4-m level)	6.0	8.2	4.5 (at 10-m level)

Each computer code was modified to permit the calculation of dosages from the pred concentration variation with time. COMBIC, ACT II, and MAD Puff were originally developed to pr obscuration calculations. The transport and diffusion portions of the code are relatively small permit the computation of concentrations with time at any receptor from which dosages (integr concentrations with time) were calculated.

All computer runs were carried out on a Ridge 32 mini-computer. There is roughly a factor of 6 greater computation time for the Ridge as compared to an IBM 3033 mainframe. COMBIC was run with one second time steps and ACT II and MAD Puff were run with one second between puff releases. The equivalent run times of the COMBIC, ACT II, and MAD Puff models for an IBM 3033 were about 10 minutes for each line of sight. Each of the models was run within its original computer code which carried out many other calculations (such as transmittance across lines of sight) that were largely irrelevant to the objectives of the present validation exercise. As a result, the run times are considerable larger than if the models were coded solely for transport and diffusion calculations with the subsequent output of dosages. The Ludwig Model was run with 10 seconds between puff releases; the computer code ran an equivalent of only 30 seconds on the IBM 3033. This model was set up directly to produce concentration predictions with time from which we prepared dosage values.

5. RESULTS OF MODEL/DATA COMPARISONS

The comparison of dosage predictions and data for the three Smoke Week trials are given in Figures 5-9. Smoke Week III, Trial 4 comparisons for LOS 3 and 2 are given respectively in Figures 5 and 6. For Smoke Week III, Trial 19, comparisons for dosage are presented for LOS 3 and 2 in Figures 7 and 8. LOS 1 predictions and data for Smoke Week IV, Trial 3 are given in Figure 9.

Examination of the comparisons reveals the following observations:

(a) For the short distances (approximately 50-150 m) involved, the predictions of the models are very similar to each other and are within factors of 2-3 of the data. This finding is not surprising considering the similar theoretical formulations of the models. It is not clear whether the similarity in predictions remains at larger distances. This latter question will be investigated.

(b) All model predictions of the peak dosage are offset from the data. This result is to be expected for COMBIC and ACT II since these models employ time-averaged meteorological data and, thereby, cannot resolve wind direction variations during the period of transport. The MAD Puff Model accounts for wind direction fluctuations in its use of σ_θ and σ_ϕ and the Ludwig model handles wind direction variations through its input of time-dependent meteorology. The Ludwig Model performs best in terms of estimating the location of the peak dosage.

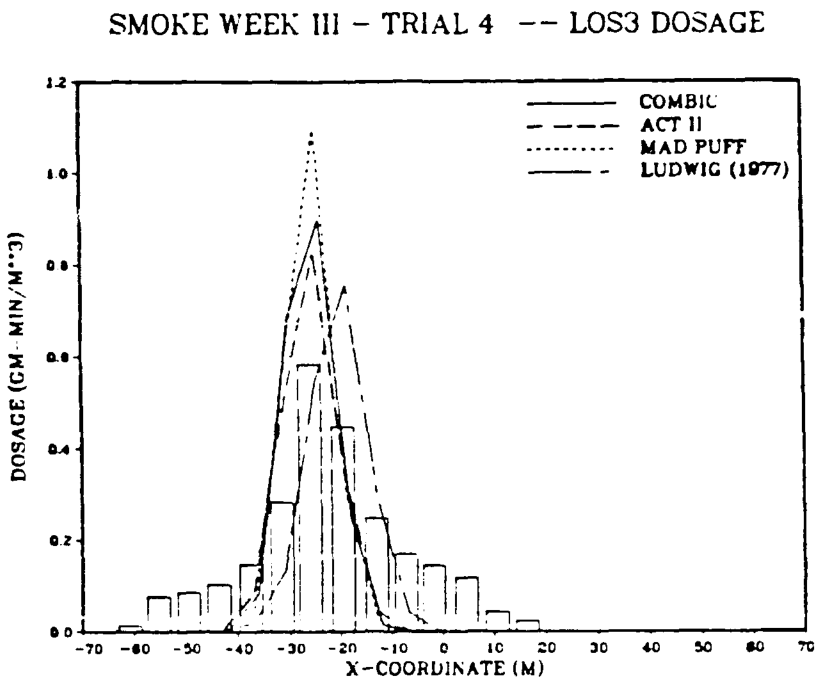

FIGURE 5. COMPARISON OF DOSAGE PREDICTIONS OF COMBIC, ACT II, MAD PUFF, AND LUDWIG (1977) WITH FIELD DATA FROM SMOKE WEEK III, TRIAL 4, LOS3

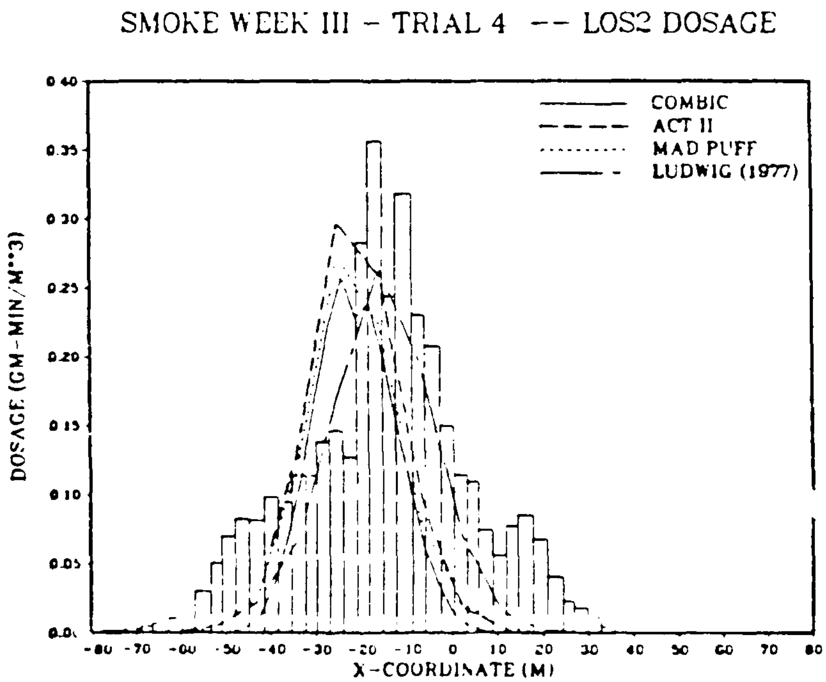

FIGURE 6. COMPARISON OF DOSAGE PREDICTIONS OF COMBIC, ACT II, MAD PUFF, AND LUDWIG (1977) WITH FIELD DATA FROM SMOKE WEEK III, TRIAL 4, LOS2

SMOKE WEEK III - TRIAL 19 -- LOS3 DOSAGE

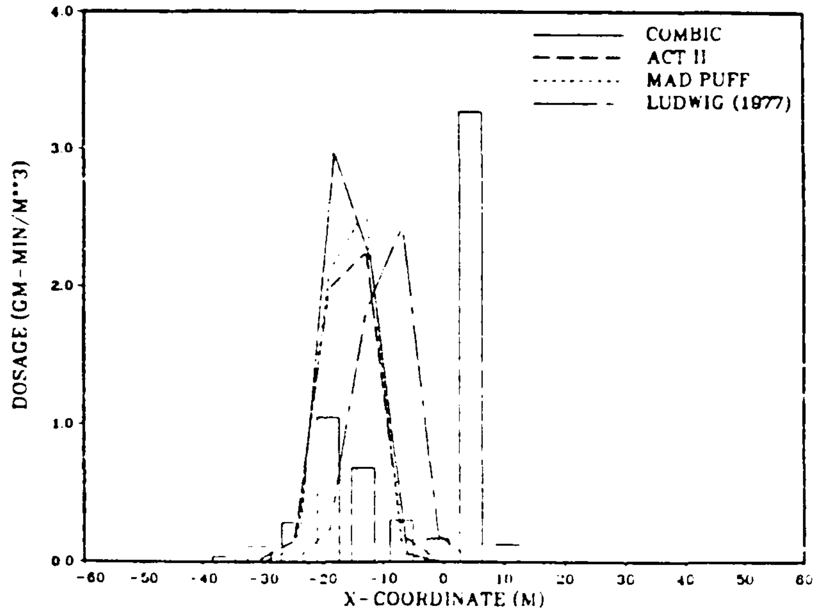

FIGURE 7. COMPARISON OF DOSAGE PREDICTIONS OF COMBIC, ACT II, MAD PUFF, AND LUDWIG (1977) WITH FIELD DATA FROM SMOKE WEEK III, TRIAL 19, LOS3

SMOKE WEEK III - TRIAL 19 -- LOS2 DOSAGE

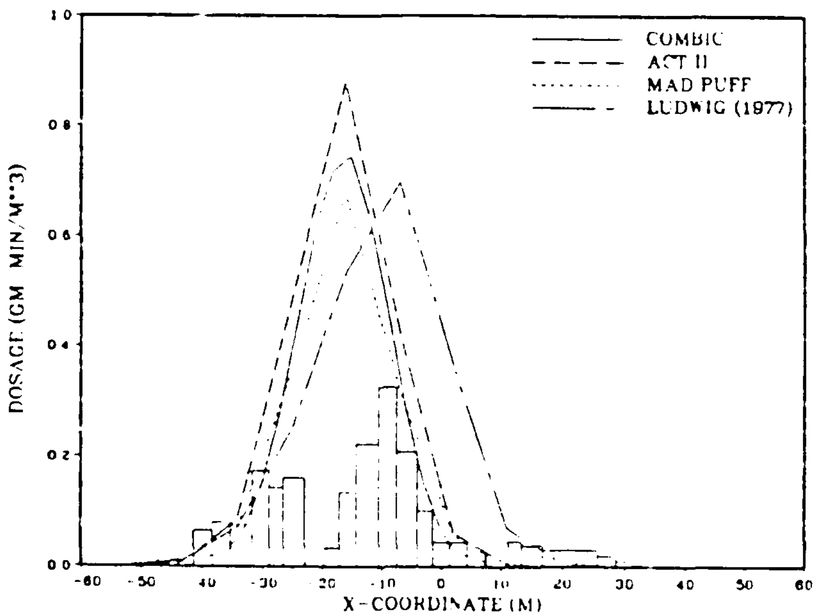

FIGURE 8. COMPARISON OF DOSAGE PREDICTIONS OF COMBIC, ACT II, MAD PUFF, AND LUDWIG (1977) WITH FIELD DATA FROM SMOKE WEEK III, TRIAL 19, LOS2.

SMOKE WEEK IV - TRIAL 3 -- LOS1 DOSAGE

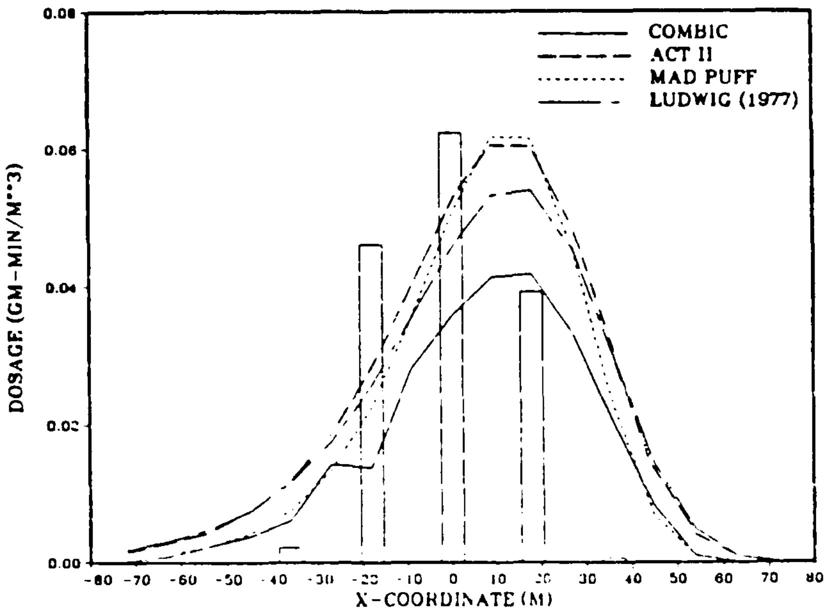

FIGURE 9. COMPARISON OF DOSAGE PREDICTIONS OF COMBIC, ACT II, MAD PUFF, AND LUDWIG (1977) WITH FIELD DATA FROM SMOKE WEEK IV, TRIAL 3, LOS1

(c) For short release times and the calculation of dosages, the randomization of puff positions (as in MAD Puff) do not appear to improve model predictions. Comparisons for further distance_ will be made in future tests.

(d) In general, the models tend to underestimate lateral spreading. This disagreement with the data may be the result of inadequate treatment of wind direction fluctuations during the period of smoke release, and

(e) The lack of data on the fog-oil release rate for the Smoke Week III tests created some uncertainty in model inputs. Apparently, the nominal 40 gal/hr rate used appeared to be a reasonable value; however, more exact comparisons of models to data require measurements of the rate of release of fog oil wit, time as well as the total fog oil consumed during generator run time. The models performed best with the data of Smoke Week IV, Trial 3; for this trial, the consumption of fog oil during the test was measured.

The data from the Smoke Week trials are very limited in quantity and distance of coverage. In fact, the three trials used in this paper were the best available from the Smoke Week tests yet they happened to have very similar meteorological conditions (stability class C, wind speeds of about 4 m/s). Additional data are required in order to make more definitive conclusions on model performance.

Future work will include:

(i) the testing of new models with Smoke Week data. Additional Smoke Week trials using fog oil will be used; however, most of the other trials involve the movement of the smoke generator during the test. Some models cannot treat this change in source location effectively within their theoretical framework.

(ii) an evaluation of the magnitude of differences in model predictions at distances in the range 500-2000 m from the smoke generator. It is to be determined whether there are greater differences in model predictions than were shown here at about 50-150 m.

(iii) a sensitivity analysis of the models to key input parameters to determine which ones require the greatest attention in the associated field program.

(iv) the development of a "generic" model in which numerous different alternative approaches can be tested within one code. In this way, the fundamental differences between modeling approaches can be compared irrespective of the details of the specific model formulation, and

(v) the testing of all models cited above with new fog oil trials presented in Dunn et al. (1985).

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